

Advanced Waste Treatment Performance Evaluation
Summary Report

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ADVANCED WASTE TREATMENT PERFORMANCE EVALUATION
SUMMARY REPORT

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FOREWORD

The U.S. Environmental Protection Agency (U.S. EPA) was created because of increasing concern about the dangers of pollution to the health and welfare of the American people. The complexity of environmental management, and the related interplay between man and the environment, require a concentrated and integrated effort to find solutions to these problems.

Over the past 15 years, the need to achieve higher efficiencies in municipal wastewater treatment has stimulated the development and implementation of various advanced wastewater treatment (AWT) technologies. The need for advanced waste treatment facilities arose when water quality goals for certain receiving waters in the United States could not be met with standard secondary treatment. Most of these complex treatment systems, numbering in the thousands, were funded by U.S. EPA under the Construction Grants Program.

Numerous studies have been conducted on the effectiveness of these technologies to meet treatment expectations. A significant number of these studies have concluded that many AWT technologies are not performing as they were designed or are not as cost effective as originally thought.

Measuring the performance of treatment technology installations under actual field conditions is an important step in finding practical solutions to the problems identified with these technologies. U.S. EPA's Office of Water Program Operations (OWPO) addresses the operational effectiveness of various technologies in wastewater treatment systems. They have compiled documentation that some AWT technologies have been applied successfully, while others have not. Furthermore, the extent to which certain AWT technologies have prevented their host treatment plants from meeting design performance or compliance goals is thought to be significant. Therefore, this evaluation was conducted to identify those AWT technologies that are experiencing chronic problems; to describe and catalog the problems preparatory to the development of specific remedial feedback information, where appropriate; and to disseminate this information.

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
	FOREWORD	ii
	SUMMARY	S-1
1.0	INTRODUCTION	1
2.0	SCOPE AND OBJECTIVES OF STUDY	3
3.0	TECHNICAL APPROACH	5
3.1	General Discussion	5
3.2	Acquisition of Data	8
3.3	Procedures and Guidelines for Evaluation	13
4.0	DISCUSSION OF OBSERVATIONS	19
4.1	Lime Handling and Feeding	20
4.1.1	Lime Loading and Unloading	20
4.1.2	Lime Storage and Dry Feeders	21
4.1.3	Lime Slaking	22
4.1.4	Lime Slurrying	23
4.1.5	Lime Slurry Transport	23
4.1.6	Lime Slurry Feed	24
4.2	Recarbonation	24
4.3	Granular Activated Carbon (GAC) Systems	25
4.3.1	Design Deficiencies	25
4.3.2	Equipment Performance Deficiencies	26
4.3.3	Operating Problems	27
4.4	Tertiary Filtration	28
4.4.1	Design Deficiencies	28
4.4.2	Operating Problems	29
	4.4.2.1 Filtration Operations	29
	4.4.2.2 Backwashing Operations	30
4.5	PhoStrip	32
4.5.1	Design Deficiencies	33
4.5.2	Equipment Deficiencies	34
4.5.3	Operating Problems	35
4.6	Biological Nitrification	36
4.7	Breakpoint Chlorination	36
4.8	Process Linkages	37

TABLE OF CONTENTS
(continued)

<u>Section</u>	<u>Title</u>	<u>Page</u>
4.9	Process Recycle Streams	37
4.10	Nonspecific AWT Related Problems	38
	4.10.1 Operating Cost Implications	38
	4.10.2 Operating Staff Needs	38
	4.10.3 Hydraulic Loadings	38
	4.10.4 Bid/Design Specifications	39
5.0	CONCLUSIONS AND FINDINGS	40
5.1	Group 1 Technologies	41
	5.1.1 Lime Handling and Feeding	41
	5.1.2 Tertiary Filtration	41
	5.1.3 Biological Nitrification	42
5.2	Group 2 Technologies	43
	5.2.1 Granular Activated Carbon Systems	43
	5.2.1.1 Independent Physical/ Chemical Treatment Systems (IPC)	43
	5.2.1.2 Granular Activated Carbon (GAC) in the Non-IPC Mode	43
	5.2.1.3 GAC Conclusions	44
	5.2.2 PhoStrip	44
	5.2.3 Recarbonation/Neutralization	45
	5.2.4 Other Technologies	45
5.3	General Observations	46
6.0	SUMMARY OF CONCLUSIONS	47
APPENDIX A	IDENTIFIED PROBLEMS, IMPACTS, AND CAUSES	A-1
APPENDIX B	SUMMARY OF PLANT CHARACTERISTICS	B-1
APPENDIX C	SUMMARY OF PLANTS BY ADVANCED TREATMENT TECHNOLOGIES	C-1

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page</u>
1	Number of AWT Facilities by Size and Design Requirements	6
2	Number of AWT Facilities in Operation by AWT Unit Process	7
3	Size Distribution of AWT Plants Selected for Visits -- Design Flow Categories	9
4	AWT Technologies Represented in Plants Visited	10
5	AWT Technologies (Task 3) -- Summary of Performance/Compliance	12
6	AWT Technologies Reviewed in Depth	14

SUMMARY

The purpose of this study is to evaluate the effectiveness of various technologies that have been used to achieve advanced wastewater treatment (AWT) objectives in municipal projects. Treatment plants known to be experiencing difficulties with their AWT processes have been investigated to determine if common problems could be identified and associated with specific AWT technologies. Common problems were identified for a number of AWT technologies and it was determined that, in many cases, these problems were serious enough to prevent the facilities from meeting their compliance or performance goals. This study attempts to identify the specific causes of these problems.

Of the more than 20 AWT technologies examined, nine were identified as having problems that need to be addressed. Several had problems so serious that complete technology reviews or additional research and development efforts may be justified. These include:

- Carbon adsorption process in the independent physical/chemical treatment (IPC) mode using granular activated carbon.
- Breakpoint chlorination.

Other processes exhibit common problems that can be mitigated through retrofit or operational modifications. These include:

- IPC systems.
- Granular activated carbon systems.
- Lime handling/feeding systems.
- PhoStrip.
- Tertiary filtration.
- Recarbonation/neutralization.

Lastly, there is one technology where only minor field changes are suggested:

- Biological nitrification.

In addition to the technical problems related to specific AWT technologies, it is also important to note other indirect problems that may be inherently associated with the use of AWT technologies. These other areas of concern include the following:

- Upsets within upstream unit treatment processes (usually conventional treatment processes) that impair performance of the AWT process.
- High cost of operating AWT systems (i.e., chemicals and power).
- Specialized training requirements for operations and maintenance staff.
- Treatment of AWT process recycle streams.
- Sensitivity to variations in hydraulic loading.
- Ability of substitute equipment or processes to meet bid/design specifications.

In order to achieve acceptable performance levels with existing or future applications of these technologies, attention must be directed to solving the identified AWT process-specific problem areas, while also considering the other indirect impacts on overall system performance.

1.0 INTRODUCTION

In 1972, Congress passed the Water Pollution Control Act Amendments (PL 92-500) from which the Clean Water Act of 1977 (PL 95-217) and the Municipal Wastewater Treatment Construction Grants Amendments of 1981 (PL 97-117) evolved. Most of the Federal financial assistance for the construction, expansion, and upgrading of municipal wastewater treatment and collection facilities in the last 10 years has been provided under this body of legislation.

The goals and policies of the 1977 Act are stated in Title I, Research and Related Programs. Of particular interest is Section 101(a)(6) which states, in part, that: "it is the national policy that a major research and demonstration effort be made to develop the technology necessary to eliminate the discharge of pollutants into the navigable waters, waters of the contiguous zone and the oceans." This policy, and related EPA program policies, became an important driving force behind the development and application of wastewater treatment processes that have the potential to remove high levels of organic, inorganic, and biological pollutants. These processes became known as advanced waste treatment (AWT) technologies; their application has been particularly appropriate for discharges to stream segments that are water-quality limited, and to other high quality water bodies. One of the most critical aspects of new technology development is the acquisition of ample and accurate performance data from large-scale demonstration facilities. However, in many cases because of the cost involved, adequate demonstration-size AWT projects were not implemented before full-scale applications were designed and constructed. Since the range of plant operating conditions that affects new technology can vary widely, an evaluation of AWT technology performance requires a technical assessment of actual large-scale operating AWT systems.

Therefore, technical feedback to designers and operators should be based on actual operating experience. This feedback can offer valuable insights relating to commonly experienced problems associated with full-scale AWT systems, particularly regarding the probable causes of these problems, and the means of avoiding these problems in future applications.

To address this need for technical feedback, the U.S. EPA has initiated an AWT technology assessment study to determine the effectiveness of various advanced treatment processes funded under the Municipal Construction Grants Program. In this assessment, the evaluation of AWT technology considers process performance (i.e., process operability and cost-effectiveness), as well as facility compliance (i.e., ability to meet design criteria and permit requirements).

2.0 SCOPE AND OBJECTIVES OF STUDY

For the purposes of this investigation, an advanced wastewater treatment (AWT) technology is defined as any unit treatment process or system that is designed to remove nutrients for meeting a specific discharge standard, and/or is designed to reduce either 5-day biochemical oxygen demand (BOD₅) or suspended solids (or both) to a level of 10 mg/L or less in the final effluent.

Advanced secondary treatment (AST) processes and land treatment systems are not included within this definition of AWT. Generally, the broad definition of AST covers those technologies designed to improve BOD and suspended solids removal in secondary wastewater treatment plants, but not to the treatment efficiencies of AWT technologies. Although it is possible for AST processes to produce effluent concentrations of BOD and suspended solids of 10 mg/L or less, this is generally not a design criterion. AST technologies are normally applied for the reduction of suspended solids, and any resulting reduction of BOD is usually incidental. AST processes have not been included in this study. Land treatment processes are not included because extensive evaluations of this technology area have already been completed. Land treatment information is readily available from EPA through other documentation, such as the Process Design Manual for Land Treatment of Municipal Wastewater (EPA 625/1-81-013).

The definition of AWT used here differs somewhat from other currently accepted definitions. The AWT treatment efficiencies specified by the definition used herein are generally more stringent than normally required. In effect, this more restrictive definition of AWT concentrates the focus of this study on those technologies associated with very high levels of treatment and the attendant problems associated with attempts to achieve these high standards.

The list of technologies for possible assessment was reviewed in light of the stated AWT definition. An inventory of all treatment plants in the country featuring these technologies was prepared and reviewed in conjunction with a review of treatment performance and compliance data for each plant. Subsequently,

candidate plants were selected for on-site AWT evaluations. Assessment reports were then prepared for each facility visited in accordance with the following objectives:

- Identify chronic problems and probable causes that adversely affect the performance of AWT technologies.
- Identify those problem areas for specific technologies that can be corrected by improved design and/or operational procedures.
- Define the implications of critical process interfaces (i.e., linkages between upstream and downstream processes).
- Identify the indirect impacts on overall facility operation, cost, and performance associated with the use of AWT technologies.

The results of these facility assessments serve as the basis for developing useful technical feedback.

3.0 TECHNICAL APPROACH

3.1 GENERAL DISCUSSION

The initial step in conducting these evaluations involved developing an inventory of installed AWT technologies on a national scale. Basic facility data (i.e., size, type of processes used, design criteria, etc.) were required to select candidate AWT plants for visitation and technology assessment. U.S. EPA provided this information through the 1982 Needs Survey and the U.S. EPA Permit Compliance System (PCS).

Using these data sources, major and minor AWT facilities that are not in compliance and/or are not performing as designed were identified. (Major facilities have been defined as those with a capacity of 1.0 million gallons per day (mgd) or greater, while minor facilities are those with a capacity of less than 1.0 mgd.) Tables 1 and 2 present a breakdown of AWT facilities by size and design requirements, and the total number of AWT facilities utilizing different unit processes. The totals shown in these two tabulations are not the same because some plants have more than one AWT unit and are, therefore, counted more than once. These lists were further screened by additional review and discussion to create a working list of 305 AWT plants, each of which appeared to be experiencing some performance and/or compliance problems.

From this list of 305 plants, 48 were selected for preliminary site visits. The plants selected for these initial site visits represented a cross-section of AWT technologies under the AWT definition used in this study. Furthermore, additional information and data were solicited from regional and state agencies to ensure that these plants were known to be experiencing operational or design difficulties with their AWT processes.

The identification of problems common to AWT processes, as observed in the various plants visited, was an important objective of this study. For a problem to be considered chronic, it had to be established as a common problem, and one that had a severe impact on facility operation.

An AWT process can experience problems of varying severity, some affecting its performance and others its compliance status. Problems associated with performance include excessive operating costs, operational complexity, basic design deficiencies, unit process mismatches, and other factors that may reduce process

Table 1

Number of AWT Facilities By Size and Design Requirements

Design Requirements	Design Size (mgd)						Total
	<0.1	0.1 - 1	1 - 5	5 - 10	10 - 100	>100	
BOD <10	3	27	10	4	3	0	47
10 ≤BOD ≤24, PHOS	6	63	57	15	27	1	169
BOD <10, PHOS	1	8	6	3	4	0	22
10 ≤BOD ≤24, TOTN	0	5	5	1	4	0	15
BOD <10, TOTN	0	0	2	2	1	0	5
10 ≤BOD ≤24, NIT	45	124	83	22	29	5	308
BOD <10, NIT	1	20	17	5	4	0	47
10 ≤BOD ≤24, PHOS, TOTN	0	1	0	2	2	1	6
BOD <10, PHOS, TOTN	1	1	4	3	2	0	11
10 ≤BOD ≤24, PHOS, NIT	7	36	43	11	21	0	118
BOD <10, PHOS, NIT	0	10	14	4	6	0	34
Total	64	295	241	72	103	7	782

BOD < 10 = BOD requirement less than 10 mg/L.

10 ≤ BOD ≤ 24 = BOD requirement 10 to 24 mg/L.

PHOS = phosphorus removal required.

NIT = ammonia removal required (nitrification).

TOTN = total nitrogen removal required (nitrification/denitrification, ion exchange, breakpoint chlorination, or ammonia stripping).

Table 2

Number of AWT Facilities In Operation by AWT Unit Process

AWT Unit Process	Design Size (mgd)						Total
	<0.1	0.1 - 7	1 - 5	5 - 10	10 - 100	>100	
1. Biological treatment							
a. Biological nitrification							
- Separate stage	11	34	52	12	23	3	135
- Combined BOD and nitrification	35	154	115	39	50	4	397
b. Biological denitrification	1	5	12	5	9	1	33
2. Physical/chemical treatment							
a. Microstrainers							
- Primary	0	0	0	1	0	0	1
- Secondary	0	4	1	0	0	0	5
b. Filtration							
- Sand	4	38	28	9	6	0	85
- Mixed media	2	10	9	4	11	0	36
- Other	0	0	3	1	0	0	4
c. Activated carbon							
- Granular	1	1	2	1	1	0	6
- Powdered	0	0	0	0	1	0	1
d. Lime addition							
- 2 Stage - Raw	0	1	4	0	2	0	7
- 2 Stage - Tertiary	1	6	4	1	4	0	16
- 1 Stage - Raw	0	3	4	3	1	0	11
- 1 Stage - Tertiary	1	11	11	8	8	0	39
e. Recarbonation	0	1	6	2	3	0	12
f. Recalcination	0	0	0	1	2	0	3
g. Alum addition							
- Primary	0	5	7	7	5	0	24
- Secondary	13	60	67	20	35	0	195
- Separate stage tertiary	2	16	15	6	8	0	47
h. Ferric chloride addition							
- Primary	0	5	7	4	5	2	23
- Secondary	0	24	25	9	16	3	77
- Separate stage tertiary	1	7	4	3	0	0	15
i. Other chemical additions	0	3	3	3	4	0	13
j. Ion exchange	1	0	0	0	0	0	1
k. Breakpoint chlorination	0	1	3	1	2	1	8
l. Ammonia stripping	0	1	2	1	2	0	6
m. Other	1	1	2	1	0	0	5
Total	74	391	386	142	198	14	1,205

operability and cost effectiveness, but not necessarily its ability to meet specific discharge limitations. Compliance problems are related to the ability of a process to reliably meet predefined pollutant removal goals. These goals are normally expressed in terms of design criteria or permit requirements.

3.2 ACQUISITION OF DATA

Table 3 shows the distribution of plant sizes selected for preliminary site evaluations. Six (or 13 percent) of the 48 plants evaluated had design flows less than 1 mgd; 58 percent of all facilities reviewed were within the 1.0 to 15.0 mgd size range. Fourteen of the plants evaluated were designed for flows greater than 15 mgd.

Table 4 lists the AWT technologies represented in all of the plants visited. As mentioned previously, the criteria applied to select these 48 plants included a preliminary knowledge of performance/compliance problems derived from actual plant operating data and supporting data from regional and state agencies, and the desire to evaluate a representative number of AWT technologies thought to be experiencing operational and maintenance difficulties. AWT technologies not experiencing significant performance problems were not studied as intensively. The distribution of the technologies evaluated, as shown in Table 4, is a result of applying these plant selection criteria.

Table 5 is a summary table showing the number of cases where an AWT process contributed to performance or compliance problems at the facilities visited. Note that the percentage of cases where a particular technology was found to contribute to problems is influenced by the number of facilities visited, which in some cases is very small. Nonetheless, the percentages shown represent a rough measure of the incidence of performance and compliance problems experienced with different AWT technologies.

It is important to note that most of the plants reviewed employed some form of biological secondary treatment (except in the case of the independent physical/chemical treatment systems) preceding the AWT processes listed in Tables 4 and 5. Furthermore, it should be recognized that the plant, as a whole, is responsible for noncompliance or nonperformance. AWT technologies that are part of a hybrid treatment system may contribute to these problems, but are not necessarily the sole cause. The intent of this study is to document the extent to which different AWT technologies are responsible for treatment facilities not meeting performance and compliance goals.

Table 3

Size Distribution of AWT Plants Selected for Visits
Design Flow Categories

Plant Size Category	Size Range Design Flow (mgd)	Number of Plants Visited
1	Less than 1.0	6
2	1.0 to 5.0	13
3	5.0 to 15.0	15
4	15.0 to 25.0	8
5	25.0 to 50.0	3
6	Greater than 50.0	<u>3</u>
Total		48

Table 4

AWT Technologies Represented in Plants Visited

AWT Technology	Number of Plants Where AWT Technology Was Used
<u>Biological Treatment</u>	
1. Nitrification	
a. Separate	18
b. Combined	6
<u>Physical/Chemical Treatment</u>	
1. Microstrainers	
a. Primary	1
b. Secondary	1
2. Filtration	
a. Sand	8
b. Mixed media	22
c. Other	3
3. Activated carbon	
a. Granular	17
b. Powdered	1
4. Lime addition	
a. Single- and two-stage (primary)	10
b. Single-stage (tertiary)	6
5. Recarbonation	8
6. Neutralization	2

Table 4
(continued)

AWT Technology	Number of Plants Where AWT Technology Was Used
<u>Physical/Chemical Treatment</u> (continued)	
7. Alum addition	
a. Primary	6
b. Secondary	5
c. Separate stage tertiary	4
8. Ferric chloride addition	
a. Primary	8
b. Separate stage tertiary	7
9. Other chemical addition (e.g., polymers)	9
10. Ion exchange (ammonia removal and recovery process (AARP))	2
11. Breakpoint chlorination	6
12. Ammonia stripping	1
13. Other	
a. PhoStrip	3
b. Post-aeration	14
c. Dechlorination	6

Table 5

AWT Technologies
Task 3
Summary of Performance/Compliance Problems

1	2	3	4
AWT Technology	Number of Facilities Evaluated	No. of Cases Where AWT Process Contributed to Performance/Compliance Problems	Percentage
Biological nitrification	24	7	29
Microstrainers	2	1	50
Filtration	33	13	39
Activated carbon	18	14	78
Lime addition	16	16	100
Recarbonation	8	7	87
Alum addition	15	2	13
Ferric chloride addition	15	2	7
Ion exchange (ARRP)	2	1	50
Breakpoint chlorination	6	3	50
Ammonia stripping	1	1	100
PhoStrip	3	3	100
Post-aeration	14	0	0
Dechlorination	6	0	0
Neutralization	2	0	0
Other chemical addition	9	0	0

The primary focus of the initial one-day site visits at each of the 48 plants was to identify chronic problems with AWT processes or systems, as they related to design, operation, and cost considerations. To standardize and facilitate the collection of data, a standard data summary format was used for all site visits. This format was followed by each investigator and the data collected was based on their observations and discussions with plant operating personnel, administrators, and design engineers. The format was designed to obtain the following information:

- General information describing the plant.
- Construction dates.
- Management/financial information.
- Hydraulic information.
- Wastewater characteristics.
- Effluent discharge information.
- Treatment facilities description.
- Equipment design and performance specifications.
- Operation and maintenance data.
- Performance problems summary.
- Preliminary performance assessment.

After the information from the initial 48 site visits was evaluated, 10 of the 48 plants were selected for more intensive 2- to 3- day reviews. These plants were selected primarily because they featured widely used AWT technologies. Furthermore, they experienced problems with their AWT processes that were considered to be chronic and typical for the AWT technologies involved.

Table 6 shows a distribution of the AWT technologies reviewed at the 10 plants selected for more intensive reviews. Generally, the number of intensive site visits made for each AWT technology presented in Table 6 is proportional to the number of plants reporting chronic problems with these technologies.

3.3 PROCEDURES AND GUIDELINES FOR EVALUATION

The information obtained in the plant visits and follow-up efforts was organized in tabular form to relate identified problems with their impacts and causes. This information is presented in Section 4 and Appendix A. This provided a means of translating field findings and observations from a specific treatment

Table 6

AWT Technologies Reviewed in Depth

AWT Technology	Number Reviewed
Lime systems	7
Activated carbon	5
Filtration	3
Recarbonation/neutralization	3
Biological nitrification	3
PhoStrip	2
Ammonia stripping	1
Ion exchange (ARRP)	1

plant orientation to a more generic technology orientation for further analysis. The parameters used to assess the extent and severity of problems identified included the following:

- The degree to which a given problem is common to a particular technology.
- Commonality of causes associated with specific problems.
- Severity of the impacts of problem areas on process performance and overall facility performance.
- The degree of interdependence of technology problem areas on other units or unit processes.

Identified problem areas are organized according to AWT or related technology categories, as follows:

- Tertiary lime addition, two-stage.
- Tertiary lime addition, single-stage.
- Lime addition to raw wastewater.
- Lime handling.
- Recarbonation/neutralization.
- Lime sludge handling.
- Tertiary alum addition, separate stage.
- Ferric chloride addition, secondary stage.
- PhoStrip.
- Biological nitrification.
- Ammonia stripping.
- Breakpoint chlorination.
- Ammonia removal and recovery process (clinoptilolite ion exchange).

- Granular carbon system.
- Tertiary filtration.
- Microstrainers.
- Process linkages.
- Instrumentation.
- Process recycle streams.
- Non-AWT processes.

It must be re-emphasized that the problems, impacts, and probable causes discussed in Section 4 have been identified from discussions with plant operating and management personnel, observations made during site visits, and data and reports made available by plant representatives. The assessment of impacts and causes, therefore, may be somewhat subjective. However, it is felt that this is an accurate representation of the chronic problems and problem causes that can have significant and direct impacts on AWT plant performance. Other secondary and more remotely-related impacts and problem causes can be identified, however, the focus of this study is to identify the primary causes and impacts for the noted chronic problem areas.

As an example of the study orientation, under the category granular activated carbon systems (GAC systems), one major problem identified was sulfide generation. The two most significant impacts on GAC plant performance and operation were reported as localized corrosion and odor production. The identified operating characteristics related to sulfide generation included BOD overload to the system, anaerobic conditions in the adsorbers, and inadequate backwash capability. These characteristics are somewhat interrelated. They were reported and/or observed for a number of plants.

To proceed further with the GAC example, equipment failure is a secondary impact resulting from the specific identified impact of localized corrosion. One of the operating characteristics associated with the sulfide generation problem is BOD overload to

the system, and was, in some cases, a result of inadequate performance of preceding process units (considered a secondary-type cause in this study). These causes were categorized as related "process linkage" factors and are discussed separately.

Under the AWT category, two-stage tertiary lime addition, one identified problem is the inability to raise process pH to the desired level. Insufficient phosphorus removal is identified as the impact of this problem, and the identified cause is a malfunction of the lime delivery system. Violation of effluent phosphorus limitations is an implied secondary impact of the identified primary impact, insufficient phosphorus removal. However, permit violations attributable to this problem are not listed as a primary impact, because documented evidence of a direct cause-effect relationship could not be obtained.

Another example that helps to illustrate the scope of these evaluations relates to the category of "process linkages." One of the identified problems in this category is the accumulation of grease on tertiary filters. The major impact associated with this problem is labor intensive operations. The causes of this problem are associated with upstream treatment processes and not with any design or operational deficiency associated with tertiary filtration per se. Therefore, the problem is listed under "process linkages" and not "tertiary filtration" because this problem is not specific to tertiary filtration technology, but rather relates to other aspects of plant design and/or operation.

Additionally, labor-intensive operation is the primary impact identified for the problem of grease accumulation on tertiary filters because of the need for frequent backwashing and constant operator attention. Poor effluent quality (high turbidity and/or TSS) can result from this problem, particularly if filter maintenance is neglected. However, as with the previous example, documented evidence linking this problem to permit violations could not be readily obtained, and therefore, it is considered a secondary rather than a primary impact.

Continuing this example, different contributing causes may be listed for a given problem. Three causes of grease accumulation on tertiary filters are noted. Each cause is associated with a separate plant. At one plant, repeated mechanical failure of the primary scum removal system resulted in grease carryover to the biological system and ultimately to the tertiary filters. A similar situation occurred at another plant except the apparent cause was uneven settling of the clarifier basin. The cause of

grease accumulation on the tertiary filters at the third plant was oily discharges from a major waste source, coupled with the lack of primary clarification facilities.

Based on the observations and evaluations summarized in Appendix A, which include the findings from the more intensive studies, a number of AWT process application problem areas and probable causes were identified. Their levels of significance to this study are based on the prevalence of the observed problems and the severity of their impact on plant performance.

4.0 DISCUSSION OF OBSERVATIONS

Plants selected for detailed investigation by using the approach described in Section 3 included a broad spectrum of AWT processes. These plants, identified by code numbers to mask their identity, are listed in Appendix B. This appendix describes the key process characteristics and effluent limitations as dictated by permit requirements and design criteria. Appendix C lists the respective plant codes of facilities using specific AWT technologies for cross-referencing purposes.

The use of AWT processes in some of the facilities evaluated dates back to 1971. On the other hand, some of the facilities evaluated are still in the early phases of starting up and shaking down AWT process operations. Of the total number of plants visited, 11 (23 percent) were independent physical/chemical (IPC) plants, i.e., those plants that do not employ biological treatment in the process train. The other plants represented a variety of hybrid treatment systems involving combinations of both advanced and conventional treatment processes.

A compilation of identified problems, impacts, and problem causes, based on observations made during the 48 preliminary site visits and the 10 intensive site visits, is presented in Appendix A. The problems listed in Appendix A are categorized according to the problem areas identified in Subsection 3.3. Based on an overall assessment of the observed problems 10 key problem areas were identified as being the most prominent, and therefore warranting further evaluation. These key problem areas are as follows:

- Lime handling.
- Recarbonation.
- Granular activated carbon.
- Tertiary filtration.
- PhoStrip.
- Biological nitrification.
- Breakpoint chlorination.
- Process linkages.
- Process recycle streams.
- Nonspecific AWT-related problems.

A more detailed discussion of technical observations related to these key problem areas follows.

4.1 LIME HANDLING AND FEEDING

Lime systems are used to support other technologies (PhoStrip, IPC, and biological nitrification). As a consequence, the problems incident to lime systems adversely affect other systems as well. The most common problems with this technology and their respective causes fall into the following six general areas:

- Lime loading and unloading.
- Lime storage and dry feeders.
- Lime slaking.
- Lime slurring.
- Lime slurry transport.
- Lime slurry feed.

4.1.1 Lime Loading and Unloading

Identified problems associated with lime loading and unloading include the following:

- A common problem experienced with loading and unloading lime is the generation of lime dust. Inhalation of lime dust causes irritation of the nose and eyes, and makes the work atmosphere very uncomfortable. The fine grit particles present in lime dust can cause severe damage to eye tissues when eyes are rubbed to alleviate the discomfort. Quicklime dust can cause burns due to the generation of heat when in contact with moisture in the eyes, nose, or mouth. Manual handling of bagged lime is a source of dust in the loading/unloading area. In the case of bulk lime handling, the problem of dust is primarily attributed to malfunctioning of the baghouses installed on top of lime storage bins. If the baghouse filters are not emptied frequently, they are unable to collect the dust, thereby causing problems. Undersized and clogged dust collection baghouses not only create dust problems but may also result in equipment damage and personnel injury due to a sudden rupture of the baghouse.

- Sharp elbows and bends in lime transport piping to the storage bin are subject to severe damage caused by abrasion, particularly when quicklime is used.
- Maintenance and repair of lime transport piping is a problem if the piping is located out of reach of personnel, or is otherwise inaccessible.

4.1.2 Lime Storage and Dry Feeders

Major problems associated with lime storage and dry feeders include the following:

- In lime storage bins, the flow of lime to the feeders is interrupted by "arching" or "bridging" above the hopper opening. Sudden "flooding" of the feed hopper occurs when the arch breaks. This problem is particularly common when powdered lime is used. Granular or pebble lime is generally a free-flowing material.
- Clogging of the feed hopper opening and feeder valve in the storage bin is another common problem. This problem occurs due to the entry of moisture into the storage bin, which causes the lime powder to "cake," thereby preventing free-flowing conditions.
- Screw-type lime feeders are difficult to operate if moisture enters the screw feeder. The lime can then "cake," with the likelihood that the screw will become jammed.
- Gravimetric feeders require frequent maintenance and are now more difficult to operate than volumetric feeders.
- Mechanisms for vibrating lime storage bins or agitating the contents to break arches and to ensure smooth delivery of lime have not been as successful as "live bin" systems.

4.1.3 Lime Slaking

Lime slaking is necessary to ensure a properly prepared hydrated lime slurry feed to the treatment process. Lime slaking involves two critical factors: an optimum slaking temperature, and an efficient system for separating nonlime materials (grit) from the slaked lime slurry. Lime slakers are classified as detention type, paste type, or ball mill type. Detention-type slakers are most commonly used in water and wastewater treatment plants. The major difference between the detention- and paste-type slakers is that a higher water-to-lime ratio is used in the detention-type slaking process. In ball-mill slakers, the lime is ground in a mill before slaking. Problems associated with lime-slaking operations are as follows:

- Undersized drives for screw conveyors results in breakage of clutch equipment.
- Accumulation of dust in and around the grit conveying system results in increased viscosity of gearbox oil, thereby requiring frequent oil changes.
- Probes used for indicating slurry levels malfunction due to encrustation and scaling.
- Cleaning of slakers for maintenance is a labor-intensive operation; encrustations of lime on tank walls, valves, and orifices normally must be manually chipped, scraped, and removed from the slaker. This cleaning problem is further aggravated if some parts of the slaker are not easily accessible.
- Instrumentation panels located on or adjacent to the slaker are often covered with dust and grit. This contributes greatly to malfunctioning of lime control systems.
- Maintaining airtight conditions in a slaking system and operating it under negative pressure is difficult. Thus, moisture from the slaker travels back to the lime storage tank causing "caking" of lime and clogging of feed hoppers.

4.1.4 Lime Slurrying

In most treatment process applications, lime is introduced as a slurry. In the slurrying operation, slaked quicklime or hydrated lime is mixed with water and agitated in a covered tank to form a slurry of a concentration suitable for feeding. Usually a 5 to 10 percent slurry concentration is used. Problems associated with lime slurrying operations are as follows:

- Probes used for level control in slurry tanks become coated with scale and are rendered ineffective.
- Maintenance of agitator motors and level controllers in elevated slurry tanks is a problem due to poor accessibility.
- A severe abrasion problem occurs if fiber-reinforced plastic (FRP) tanks are used for lime slurry preparation, particularly when quicklime is used.

4.1.5 Lime Slurry Transport

Transportation of lime slurry presents one of the most difficult problems in a lime handling system, as noted here:

- Scaling of pipes is a severe problem common in most lime slurry transport systems. Scaling may be caused due to the following conditions:
 - Leakage of air into pipes around the pump seals or through other appurtenances. Carbon dioxide in the air reacts with lime to precipitate calcium carbonate as scale on the inner walls of pipes.
 - Settling of solids from the lime slurry during off cycles.
- Small diameter piping is reported to be one of the major causes of frequent clogging of lime slurry transport pipes.
- The problem of scaling and deposition of solids in sharp bends and elbows is very common in lime slurry transport lines. Right-angle bends at the bottom of vertical pipes are extremely prone to the deposition of lime solids.

- Cleaning of scale accumulated in lime transport lines is extremely difficult and labor intensive, particularly when metal pipes without cleanouts are used. The problem is more severe in long lengths of transport lines.

4.1.6 Lime Slurry Feed

The controlled addition of lime slurry to a treatment process is generally carried out using feed pumps and control valves. Problems experienced with lime slurry feed systems are as follows:

- Lime slurry feed systems are faced with the problem of scaling and clogging of pumps and metering valves. Clogging is particularly common when the feed system is used intermittently.
- Progressive cavity type metering pumps have high maintenance requirements due to stator wear.
- Slurry feed metering valves with variable flow rate control are easily clogged due to lime deposits in constricted areas of the valves.
- A common problem with pH-controlled feed systems is encrustation of the pH probe (with lime solids and calcium carbonate scales) resulting in erroneous pH readings and thus improper dosages of lime to the process.

4.2 RECARBONATION

The most common problems noted with this technology appear to be the following:

- Inadequate carbon dioxide (CO_2) delivery rates due to flue gas delivery malfunctioning.
- Solids accumulation in the recarbonation basin due to no solids collection mechanism and excessive scaling.

4.3 GRANULAR ACTIVATED CARBON (GAC) SYSTEMS

The GAC technology, when applied either as an integral part of the IPC systems or as a unit process operating after biological removal processes in a treatment process train, also experienced a broad range of problems in the sample of AWT plants reviewed.

4.3.1 Design Deficiencies

The efficiency of soluble BOD removal by GAC has been debated for several years. The most frequent criticism of GAC is that it cannot remove sufficient soluble BOD to meet effluent requirements, both when used as a secondary process and when used as a tertiary process.

Several factors can affect the adsorption rate of soluble organics by activated carbon. These factors include the following:

- GAC influent BOD and suspended solids concentrations.
- The nature of the carbon itself (adsorptive capacity, regeneration characteristics, and structural properties).
- The characteristics of the material to be adsorbed, including its molecular size and polarity.
- The wastewater characteristics, especially its pH.

Design deficiencies also cause physical problems that may affect process performance. For example, corrosion and abrasion of carbon systems are serious problems that have been observed in a number of plants. Dry carbon is not corrosive; however, partially dewatered carbon is extremely corrosive. Under conditions of continuous exposure, it may produce pitting in unprotected mild steel plate by electrolytic corrosion at a rate as high as 250 mils per year. Abrasion of pipelines by carbon slurry can also be a problem with steel pipes. Abrasion is greatest at bends and in uncoated steel pipe.

In addition to corrosion and abrasion problems, other carbon handling problems have occurred at 28 percent of the plants visited. These problems include the following:

- Clogging of carbon transport pipes.
- Plugging of upflow packed carbon beds.

The causes of these problems are primarily design-related and are as follows:

- Undersizing of carbon slurry and water lines.
- Poor carbon transport system design, i.e., use of short radius and 90° elbows.
- Lack of cleanouts in the carbon transport system.
- No eductors provided to slurry the carbon from the contactor.
- Design of an ineffective backwash system.
- Insufficient backwash frequency in automated systems.

Structural design problems with GAC systems have occurred at some plants. These problems have included underdrain structural failure and ruptured adsorber influent pipes. The causes are poor structural design, higher than anticipated structural loadings, equipment furnished not in accordance with engineer's specifications, and improper installation.

Another observed design problem relates to the use of carbon for dechlorination following breakpoint chlorination for ammonia removal. The identified causes indicate that the carbon systems used for this purpose were improperly sized and/or evaluated in the pilot or process design phase, causing ineffective dechlorination under full-scale conditions.

4.3.2 Equipment Performance Deficiencies

Two equipment performance deficiencies were identified during the AWT assessment, as follows:

- Unreliable regeneration furnace exhaust systems.
- Excessive carbon charring in the regeneration furnaces.

These problems were caused by mechanical failure of the exhaust fan and clogging of the carbon slurry pumps, which causes the carbon to back up in the furnace. (The carbon regeneration system and related problems are not discussed here. The interested designer or operator is, however, cautioned to be aware of these deficiencies, and is encouraged to evaluate them in depth.)

4.3.3 Operating Problems

The most common problem reported for the GAC systems visited, with the exception of the soluble BOD removal problem, was hydrogen sulfide (H_2S) generation. This problem was primarily found in IPC mode GAC systems, but did occur in tertiary systems as well.

Hydrogen sulfide gas develops when sulfates present in the influent wastewater are biochemically reduced by sulfate-reducing bacteria under anaerobic conditions. Conditions promoting or accelerating hydrogen sulfide production in GAC contactors include the following:

- Low concentrations or the absence of dissolved oxygen and/or nitrates in the GAC system influent.
- High concentrations of BOD and sulfates in the GAC system influent.
- Long detention times.
- Low flow-through velocities.

Other reported operating problems were clogging of backwash and/or surface nozzles, and spent carbon rotary feed system malfunctions. Carbon media and/or solids that leave the contactor are responsible for clogging the nozzles and wash mechanisms. If the carbon can be prevented from migrating to the contactor underdrains (due to failures in the media support system), it will not be picked up by the incoming backwash water and clogging of the distribution nozzles can be averted.

4.4 TERTIARY FILTRATION

This technology also appears to be affected by a broad range of problems. Moreover, these problems are fairly evenly distributed between design deficiencies and operational difficulties. The most common of these problems are discussed in the subsections that follow:

4.4.1 Design Deficiencies

Design deficiencies associated with tertiary filtration include the following:

- Frequent clogging of the media and buildup of excessive head loss. This problem results in short filter runs and increased demands for backwashing.
- Operating difficulties and poor effluent quality are often consequences of hydraulic surges in the influent flow to filters caused by insufficient flow equalization.
- Backwash systems designed to initiate operation on the basis of a single criterion, namely, either a fixed time interval or a predetermined head loss, sometimes result in improper frequency of backwash.
- Excessively high flow rates during backwashing can cause loss of media, additional hydraulic load on the processes receiving recycled backwash water, and depletion of water supply for subsequent backwashing operations.
- Uneven distribution in layout of washwater troughs on the filter bed creates differential velocity gradients, causing carryover of sand media during backwashing.
- Improper design of the filter underdrain system causes migration of filter media to the underdrains and clogging of backwash nozzles.
- Improper selection of the materials of construction for backwash nozzles results in corrosion, dislodging from their support structures, and inadequate backwashing.

4.4.2 Operating Problems

The following discussion of operating problems is divided into two categories: filtration operations and backwashing operations. The filtration operations section discusses problems that develop during the processing cycle. The backwashing operations section details problems that arise during the backwash cycle.

4.4.2.1 Filtration Operations

Problems associated with filtration operations include the following:

- Media clogging is a widespread filtration problem that increases the head loss through the bed and thus decreases the length of the filter run. Certain clogging problems are the result of ineffective backwashing. These problems are discussed in the subsection on backwash operations. Media clogging can also result from the following:
 - Microbial growth in the filter bed.
 - Solids carryover from prior treatment processes, especially when previous process upsets occur.
 - Oil and grease carryover from prior treatment processes.
 - Precipitation of calcium carbonate, magnesium sulfate, calcium sulfate, etc. on the filter bed due to malfunctioning of a prior unit treatment process. This precipitation can occur particularly when the wastewater has been treated with lime at a high pH, and recarbonation/neutralization is not carried to completion.
- Maintenance operations at many treatment plants are not adequate to keep the filter system functioning properly. Insufficient maintenance can result in nonfunctioning or ineffective instrumentation systems and inoperative valves and pumps, etc. These systems impact filter operations and can cause the system to discharge a poor quality effluent.

- Many operators have received little or no formal training in the operation of filtration systems. This lack of knowledge and training can cause ineffective filtration and inhibit operators from making the alterations necessary to improve filtration operations. This inflexibility can compound problems during periods of process upset with prior treatment processes.

4.4.2.2 Backwashing Operations

The purposes of filter backwashing is to remove the foreign material collected on the filter bed during the preceding filter run. Problems associated with filter backwashing are as follows:

- Incorrect sequencing of backwash pumps can cause the following problems:
 - Incomplete backwashing with resultant reduced filter run durations. Auxiliary backwashing procedures, such as surface-water agitation, air scour, or subsurface agitation systems, should occur during the initial fluidization stage of backwashing. If the auxiliary equipment does not operate, backwashing will not be effective and much of the foreign material will not be removed from the bed.
 - Filter media loss. Auxiliary backwashing equipment provides agitation and mixing in the filter bed during the initial or fluidization stage of backwashing. If the auxiliary air scour is operated when the backwash water is flowing into the troughs, media loss will occur.
- Maintaining the proper rate and duration of backwashing can be a problem. If the backwash rate and/or duration is not sufficient, the bed will not be thoroughly cleaned. This problem occurs more frequently in warmer weather due to the decreased viscosity of water at higher temperatures. Filter clogging and mudballs can occur if insufficient backwashing rate or duration continues. These problems lead to decreased filter effectiveness. Conversely, too high a backwash rate because of an incorrect setting on a backwash system with no rate limiting control can result in media loss, gravel mounding, or gravel displacement.

- Media clogging, mudball formation, media loss, and gravel mounding and displacement result from incorrect filter backwashing. A brief description of these impacts follows:

- Media clogging results from solids buildup within the filter bed. This solids buildup increases the head loss through the filter bed and, thus decreases the length of the filter run. Shorter filter run times will increase the number of backwashings required, which in turn will decrease the filter's hydraulic capacity and increase operating costs.
- Mudballs are agglomerations of biological floc, dirt, and the filtering media. These mudballs can grow into large masses, sink into the filter bed, and eventually reduce the effectiveness of filtering and backwash operations.
- Media loss in a filter bed will result in a faster buildup of head loss in the bed, and reduced filter run times in multimedia filters especially. This is primarily due to the loss of lighter, coarser media from the top layer of the bed. In single media filters, the loss of the fine media layer on the top could be reflected in inferior quality of effluent. Media loss can also affect backwash operations. Auxiliary wash or scour systems are set to operate at certain levels within or above the filter bed. When media loss occurs, the levels at which the auxiliary system were set are no longer correct for effective backwashing. Media loss can also result in clogging and erosion of backwash nozzles and pumps. Some plants save the last portion of their backwash water for use in subsequent backwashings. But the lost media is in the water that is used for subsequent backwashings. This media can clog and/or erode the backwash pump and nozzles.

- Gravel mounding results when the various layers of the support gravel are disrupted by excessive flow rates during backwashing. When mounding occurs, the filter must be taken off line and the support gravel and media leveled. If the mounding is severe, or the gravel is displaced into the media, the filter media may have to be regraded or replaced.

4.5 PHOSTRIP

The PhoStrip^R system is a proprietary process¹ involving sidestream biological and chemical treatment for the removal of phosphorus. It may be a cost-effective process alternative to be used in place of the conventional method of metal or mineral addition using alum or iron salts or lime for phosphorus precipitation. Since the early 1970's, the concept behind PhoStrip has been well developed and the process has been employed in nearly a dozen treatment facilities. However, a significant number of these plants appear to have difficulty in consistently producing effluent quality of less than 1 mg/L total phosphorus (TP) as intended. Most of these plants have also experienced considerable startup problems. Available data indicate that when the PhoStrip process is used for treating typical domestic wastewater, it is capable of producing an effluent total phosphorus (TP) of 1 mg/L, provided the facilities are properly designed and operated.

The PhoStrip process has been employed in 10 full-scale municipal plants (other plants in the design or construction stage are not included in this counting). Four of these plants discontinued the use of the PhoStrip process for various reasons, while six of these plants are still employing the process. Most of these plants are producing an effluent TP concentration of less than 1 mg/L on an average basis. However, few of these plants can consistently meet the 1 mg/L TP requirement by using only the PhoStrip process due to a variety of factors. Since a significant portion of TP exists in the suspended solids form, effluent filters are provided in 5 of the 10 PhoStrip plants in order to produce more consistent effluent quality. Major reasons for poor process performance are related to design deficiencies, equipment deficiencies, and operating problems, many of which have been encountered in new wastewater treatment facilities.

¹Biospherics, Inc., Rockville, Maryland.

4.5.1 Design Deficiencies

The following design deficiencies have been experienced in one or more of the plants employing the PhoStrip process:

- Failure to account for variability in influent flow and wastewater characteristics during design. (This can interfere with the anaerobic-aerobic sequencing mechanism and cause effluent quality to fluctuate.)
- Lack of pumping capacity and the inability to divert a significant percentage of the sludge recycle stream through the PhoStrip process to allow operators to control the solids residence time (SRT) in the anaerobic stripper. (Uptake of phosphorus in the aeration basin cannot function properly unless the sludge is adequately preconditioned in the "anaerobic stripper.")
- Lack of provision in the piping to bypass the primary clarifiers if necessary. (When influent wastewater is weak in organic strength, the use of primary clarifiers can increase the degree of nitrification in the aeration basin, which can subsequently interfere with the anaerobic treatment process.)
- Deficiency in the design of the elutriate stream piping system, such as directing flow over a conventional weir launder or dropping the flow from a pipe, which permits aeration of the liquid. (Introduction of dissolved oxygen into the anaerobic stripper results in retarding the release of phosphorus.)
- Lack of flexibility in the piping system to allow operators to select primary effluent as an alternate source of elutriate water. (The solids residence time in the anaerobic stripper could become insufficient if the reactor-clarifier effluent, which is low in organic strength, is used as the elutriate water.)

- Lack of piping to divert the sidestreams, such as supernatant from sludge thickeners and filtrate from dewatering facilities, directly to the PhoStrip reactor-clarifier. (These sidestreams may contain high concentrations of phosphorus due to uncontrolled release under anaerobic conditions and, if returned to the front-end of the plant or aeration basins, could affect the effluent quality of a system that may perform marginally at times.)

4.5.2 Equipment Deficiencies

There are a number of deficiencies in the equipment used in conjunction with the PhoStrip process, but not supplied by Biospherics, Inc., even though the equipment used is considered mostly conventional wastewater treatment equipment and is not unique to the process. These deficiencies include the following:

- Automatic control of SRT in the anaerobic phosphorus stripper was not possible due to:
 - Failure of the sludge density meters and/or sonic flow meters used to monitor the various flow streams in the PhoStrip process.
 - Failure of the level indicators to detect the sludge blanket interface.
- Faulty system instrumentation related to pH control and flow meters, and problems with computer control during startup.
- Frequent fouling of pH probes resulted in overdosing or underdosing of lime to the reactor-clarifier. This caused the feeding of lime to be operated in manual mode much of the time.
- Breakdowns of gear boxes for sludge scraper mechanisms used in the anaerobic strippers and failure of motor drives due to improper calculation of torque requirements.
- Severe plugging problems in the effluent launders of some reactor-clarifiers constructed with submerged orifices.

- The elutriate header in a stripper tank became clogged upon shutdown of the elutriate pumps because it was installed with the orifices facing upward.
- Malfunctions occurred in some of the electrical and instrumentation equipment because enclosures and conduit connections were not weatherproof, resulting in moisture due to condensation.
- Numerous problems associated with the lime feed and lime sludge handling systems.

4.5.3 Operating Problems

The operating problems encountered are caused by a combination of factors, including those caused by design and equipment deficiencies, lack of piping flexibility, and removal of some major process units or instrumentation from service, which caused difficulties in realizing the full phosphorus removal potential of the PhoStrip process. Some of the specific problems include the following:

- Optimizing the relative removal of phosphorus from the two possible exit points in the process; namely, through wasting of excess activated sludge from the secondary clarifier underflow, and by chemical precipitation of phosphorus in the anaerobic stripper supernatant, can be very time consuming and labor intensive.
- The concern over the degree of nitrification, which can be caused by low influent BOD, long sludge age in the system, and warm weather conditions, adds to the complexity of PhoStrip plant operation since high nitrate concentrations interfere with the mechanism of phosphorus release in the anaerobic stripper.
- In one case, extensive manual monitoring was required to properly control SRT in the stripper since sludge density meters, sonic flow meters, and sludge blanket interface indicators, all ancillary to the PhoStrip scope of supply, were inoperative.

- The pH probes installed in the reactor-clarifiers were easily fouled, causing the automatic lime slurry feed system to malfunction. It was difficult to maintain a specific pH with manual control of the lime feed system.
- Calcium carbonate scaling reduced the capacity of some of the system piping and caused severe plugging problems, particularly with the elutriate line between the reactor-clarifier and the stripper tank.

4.6 BIOLOGICAL NITRIFICATION

The biological nitrification systems studied had relatively few problems, and these were widely distributed. Two problems that appear to be common are the following:

- Alkalinity is required in the biological nitrification process and is often supplied by lime. Many of the problems concerning the lack of sufficient alkalinity or low pH relate to difficulties with lime addition.
- An acclimated biomass is critical to the proper functioning of the biological nitrification process. This is true of both suspended growth and fixed film reactors. In cases where it is difficult to control hydraulic loading, an unusually high loss of solids to carryover or sloughing can adversely affect process efficiency.

4.7 BREAKPOINT CHLORINATION

This technology experiences chronic problems that severely impact plant performance. The most important problems observed are the following:

- The process is inclined to produce high residual chlorine concentrations in reaching breakpoint. If the chlorine dosage is improperly paced, the residual will be variable and dechlorination will be ineffective.
- Nitrogen removal by breakpoint chlorination is costly. Moreover, the costs primarily impact operating budgets. This makes the process unpopular with treatment plant owners.

- The impact of trihalomethane formation in receiving waters, although not performance related, is a problem that hampers the more widespread use of this process.

4.8 PROCESS LINKAGES

Process upsets within, and inadequate design and operation of, conventional unit treatment processes can adversely affect the operation of downstream AWT processes. This often requires more operator attention and more process "fine tuning" with the conventional unit processes than would be necessary if AWT processes were not a part of the overall treatment system.

Therefore, these process linkages cannot be ignored in assessing the performance of AWT systems. In Appendix A, nine problems were noted in this category. The two following general linkage problems are considered to be serious and common, within the limits of the data base assembled for this study:

- Secondary solids carryover to a tertiary system due to uneven mixed liquor flow distribution, constraints on secondary solids removal capacity, poor biological system control, clarifier short circuiting, and solids gasification or sloughing.
- Grease accumulation on tertiary filters due to mechanical failure of the scum removal mechanism or no primary separation facilities.

4.9 PROCESS RECYCLE STREAMS

Return supernatant from digesters, decanting or off-streams from conventional (e.g., heat treatment processes) or AWT unit treatment processes (e.g., PhoStrip) in a wastewater treatment plant usually contribute a significant materials loading on the forward flow treatment system. The most important of the related problems observed in this study include the following:

- Biological process upsets due to high organic loading from a sludge heat treatment process.
- High pH in lime-conditioned filtrate from a sludge dewatering operation.

- Increased phosphorus loadings due to digester supernatant return.
- Upsets in both biological treatment and solids separation due to high temperatures from incinerator scrubber water recycle and carbon regeneration scrubber water recycle.

4.10 NONSPECIFIC AWT RELATED PROBLEMS

4.10.1 Operating Cost Implications

One consideration affecting the operability of granular activated carbon is the financial implications of its operation over time. It is evident in several installations that the time period between project planning and startup/operation was so long that operating costs were grossly underestimated during the design stage, even allowing for inflation. The wastewater treatment plants so affected did not have an adequate budget to fully operate their AWT systems.

4.10.2 Operating Staff Needs

When the more complex AWT processes, such as granular activated carbon, breakpoint chlorination, and recarbonation are installed in small-sized facilities, the problem of acquiring and keeping qualified operators is very acute and one not easily resolved. The operators at smaller facilities are often not formally trained for the more complex processes. If they are fully trained or experienced, they may be tempted to leave for jobs at larger treatment plants where the pay is better.

4.10.3 Hydraulic Loadings

Observations made during the course of this study confirm the cause and effect relationship between excessive and/or variable hydraulic loadings and AWT processes. When flow exceeds treatment plant capacity, unit process upsets are likely to occur in both conventional and AWT unit processes.

4.10.4 Bid/Design Specifications

In cases where key AWT processes are bid to a performance specification, the use of the "or equal" clause in the bid specifications imposes a significant responsibility on the engineer. This is, of course, especially true when a new, complex, and/or equivalent AWT process is seeking to gain acceptance under the "or equal" clause. The law requires that the engineer also consider this process. On the other hand, a judgment must be made to qualify the equivalent process on the basis of whatever pilot- or full-scale operating data are available. Often sales claims exceed actual performance and the knowledge or experience of the engineer is inadequate to render a proper qualification decision. Three plants were observed during this study as having been affected significantly by this problem. It is clear that more specification and equipment/selection guidance is needed to allow the designers to address this problem satisfactorily.

5.0 CONCLUSIONS AND FINDINGS

This section summarizes the observations reported in Section 4 and, more specifically, the data in Appendix A. It provides conclusions about AWT technologies that reflect the study objectives, as stated in Section 2.

The AWT technologies that have chronic performance problems, justifying the development of remedial solutions and new design criteria for future applications, are classed into the following two groups:

- Those with relatively broad application.
- Those with relatively limited application.

For purposes of this study, Group 1 technologies include those that are popular and widely implemented in terms of absolute numbers in existence. These include the following:

- Lime handling and feeding, and associated lime sludge handling.
- Tertiary filtration.
- Biological nitrification.

In Group 2, more limited application technologies are the following:

- Independent physical/chemical treatment (IPC).
- Recarbonation/neutralization.
- Granular activated carbon in a non-IPC mode.
- Clinoptilolite ion exchange (ARRP).
- PhoStrip.
- Breakpoint chlorination.
- Microstrainers in a tertiary mode.

It should be pointed out that, although technologies in Group 2 are not widely implemented, the kinds of problems they exhibit and their implications regarding present and future applications tend to amplify their significance. Notable examples of this are IPC, granular activated carbon in the non-IPC mode, and the PhoStrip process.

5.1 GROUP 1 TECHNOLOGIES

5.1.1 Lime Handling and Feeding

The 16 plants surveyed in this study employing lime addition for phosphorus removal or neutralization have reported a significant number of problems associated with this process. As noted in Appendix A, the majority of those problems and identified causes are related to lime handling and feeding, which are not exclusively AWT processes. However, the frequency of problems reported and the variety of causes identified indicate a need to disseminate information on the unique problems of lime handling and feeding, and on effective practical solutions to those problems.

Lime handling and feeding systems, although not AWT processes, are widely used to support AWT applications and other conventional wastewater treatment applications, as well. The proper functioning of these systems, therefore, is important to the operation of dependent AWT unit processes.

Of all the treatment processes addressed in this study, lime handling and feeding exhibits the widest and most common array of problems associated with its functioning. In general, though, the problems that were observed lend themselves readily to operational and/or design revision.

All of the plants featuring lime handling and feeding systems that were reviewed in this study have experienced problems severe enough to affect overall plant performance either directly or indirectly. Existing lime handling and feeding systems can be modified at moderate capital and operating costs to perform significantly better than the observed norm. New systems designed to obviate observed problems would be modestly more expensive to implement than many of the systems reviewed in this study. It should be emphasized, however, that increased operator attention, especially in the case of pH probe maintenance, must be viewed as a critical requirement of this process if a lime addition installation is to be successful.

5.1.2 Tertiary Filtration

Thirty-three plants in the survey sample employed sand or multimedia filtration in an AWT application. Eleven of these reported problems with causes related to design, installation, mechanical equipment, and operating factors. The process is so broadly applied, and usually so essential to the satisfactory performance of AWT plants, that identification and documentation of corrective design and remedial operating measures are justified.

Tertiary filtration processes exhibit a variety of problems related to both design and operation. Most of the problems, however, specifically relate to operational aspects of backwashing. Generally, the problems observed are amenable to correction by simple retrofitting and operational modifications.

A significant number of the tertiary filtration processes reviewed in this study adversely affected the performance of their host treatment plants. An analysis of the identified causes suggests that the problems can be rectified at modest increases in both capital and operating expenditures. With the suggested feedback modifications, this process can be expected to perform significantly better than observed in this study.

5.1.3 Biological Nitrification

Of 24 plants surveyed that used biological nitrification in either a single-stage or separate-stage mode, seven reported significant problems affecting performance. These included difficulty in maintaining pH, as well as certain hydraulic-related factors. Because of the rather broad application of these processes, and their key role in achieving control of ammonia nitrogen, consideration of their problems is warranted.

Perhaps more so than others, this technology is considered operationally sensitive. The reported problems, therefore, should be given serious operational attention, as their potential burden to an operator could be significant. The problems afflicting this technology, although potentially serious, are considered solvable on a field improvement basis.

Many of the difficulties experienced with this process are related to the system's alkalinity levels when lime is used. For the most part, however, the process was found to be highly effective. Changing from lime addition to an alternate source of alkalinity should not be difficult, but will necessitate a moderate increase in both capital and operating expenses. This change will result in substantially better alkalinity control. Improving an existing lime handling and feeding system, however, is a viable alternative that may be cost-effective. (In the few cases where hydraulic problems were evident, rectification of these problems will entail significant capital cost expenditures, but will result in a more consistently effective treatment operation.)

5.2 GROUP 2 TECHNOLOGIES

This group of technologies is more limited in the number of applications than the Group 1 technologies. With the exception of IPC, the number of facilities surveyed that incorporated the use of each process ranged from two to five plants. The prevalence of related problems and the critical role of these processes in plant performance and compliance provided sufficient justification for considering these technologies for problem solutions development. Exceptions to this are technologies that are not widely used and that have poor prospects for future installation.

5.2.1 Granular Activated Carbon Systems

5.2.1.1 Independent Physical/Chemical Treatment Systems (IPC)

IPC is a treatment system that employs various combinations of AWT technologies. Although it is often characterized as a single technology, the reported performance or compliance problems at IPC plants are commonly attributable to the use of granular activated carbon for organic removal (BOD reduction), as well as to the high degree of interdependence between unit processes in the system. These unique characteristics place IPC systems in a special category for problem solutions development.

Of the 11 IPC plants studied, eight have reported an inability or difficulty in meeting design performance and effluent limitations. Because the problems are compliance oriented, as well as performance oriented, the operating or modification cost implications are substantial, if the technology cannot be made to meet the treatment levels for which it was originally designed.

5.2.1.2 Granular Activated Carbon (GAC) in Non-IPC Mode

Granular activated carbon was included in 19 plant designs in the survey group, including the 11 IPC plants. Significant problems affecting performance and compliance with effluent criteria were reported by at least 12 plants. At four of the plants, the GAC process had been abandoned/dismantled or was not being operated. Problems with this process were attributable to a wide variety of causes, from design through operation. Identified problems are related to adsorber, carbon transport system, and regeneration facility designs and/or operations.

5.2.1.3 GAC Conclusions

Problems associated with the use of granular activated carbon either as a tertiary treatment process or as an integral unit treatment process in IPC systems are predominantly the result of design deficiencies. Furthermore, the questionable ability of granular activated carbon to remove soluble BOD to AWT levels suggest that its use in IPC systems should not be continued without additional technical development and process reevaluation. On the other hand, the use of granular activated carbon in a tertiary treatment process mode seems appropriate. Problems in this context and their solutions are considered amenable to dissemination by feedback documentation to interested persons.

Although the effectiveness of IPC technology is questionable, existing systems can be modified at substantial expense in both capital and operating costs with good to excellent performance anticipated after retrofit. Modifications to a GAC system used as a tertiary treatment process, as outlined herein, would entail a moderate increase in capital and operating expenditures with significantly better results expected than those observed in this study.

5.2.2 PhoStrip

Of the plants surveyed in this study, three used the PhoStrip process, a proprietary method of biologically removing phosphorus to levels in the 1 mg/L range. Problems with this process were related to the auxiliary lime handling and feeding systems, as well as impacts on the process itself, (e.g., the effects of nitrates in the return sludge).

When viewed in context of its ability to remove total effluent phosphorus to a level of 1 mg/L, this proprietary process is considered effective if the wide variety of design, equipment, and operational problems that were observed can be addressed satisfactorily. The nature of these problems is such that they can be largely resolved by relatively straightforward design and operational modifications. Appropriate solutions should be developed and disseminated through technical feedback to designers and operators.

Moderate capital expenditures would be required to address the problems identified with this technology. It is believed that good to excellent results can be expected if the feedback recommendations are adopted.

5.2.3 Recarbonation/Neutralization

Of the 10 plants surveyed that employ recarbonation/neutralization, six reported operating problems. The most frequently reported problems related to the availability or reliability of the carbon dioxide supply for recarbonation (often supplied from incinerators or other flue gas sources). The overall effectiveness of this process affects the capability to stabilize and neutralize plant effluent.

Inadequate CO₂ delivery is classified as the most serious problem with this equipment because it interferes with the primary mission of this process.

The problem noted with this technology can be adequately addressed in a feedback information bulletin. A moderate capital expenditure would be required to rectify this problem. Excellent results can be expected as a result of stabilizing the carbon dioxide source of supply.

5.2.4 Other Technologies

Other technologies in Group 2 also exhibited serious problems. However, their relatively small numbers minimizes the need for wide-scale dissemination of problem solutions, as compared to the Group 1 technologies. Technical data and assistance pertaining to applications of these technologies are available from the respective manufacturers of these technologies or design engineers. In some cases, however, the problems associated with these technologies reflect negatively on the performance and cost-effectiveness of these processes and may discourage their future widespread use.

An example of one such technology is breakpoint chlorination. However, since this process is one of the most effective for nitrogen removal applications, further research should be devoted to determining if the serious operational problems identified can be resolved.

Other technologies in this situation are even more limited in terms of their prospects for future implementation and, consequently, do not warrant further study at this time. These include clinoptilolite ion exchange (ARRP), ozonation for disinfection, and microstrainers in a tertiary mode.

5.3 GENERAL OBSERVATIONS

It is apparent that the functional success of each AWT technology considered in this study is influenced to varying degrees by factors extraneous to the process itself. These include factors that impact the technology indirectly, like inadequate operation and maintenance budgets, as well as factors that impact the technology directly by interfering with its function, e.g., where an upstream treatment unit fails to achieve the necessary degree of pretreatment. Extreme fluctuations in hydraulic loading were also found to have a direct impact on the performance of AWT processes. Finally, it was discovered that deviations from the original design (i.e., modification of bid specifications) cause some AWT facilities to fall short of performance expectations.

These general observations point out the need to carefully consider all factors that may directly or indirectly impact the performance of the total treatment system, while considering its long-term cost-effectiveness.

6.0 SUMMARY OF CONCLUSIONS

The preceding sections identified nine AWT technologies with problems serious enough to warrant further attention by plant engineers and operators. However, some of these technologies have such a broad range of problems that only a complete technology review will help ensure their future successful application. Other AWT technologies exhibit important common problems, which lend themselves to retrofit or operational modifications by the designers and operators. Still others exhibit problems of minor consequence that can be easily coped with in the field.

These technologies have been, therefore, subcategorized as follows:

- Technologies nominated for a complete review and/or further development:
 - Process aspects of granular activated carbon in the IPC mode.
 - Breakpoint chlorination.
- Technologies nominated for improvement by design/operation feedback modifications:
 - IPC systems.
 - Nonprocess aspects of granular activated carbon.
 - Lime handling and feeding systems.
 - PhoStrip.
 - Tertiary filtration.
 - Recarbonation/neutralization.
- Technologies nominated for improvement by field changes:
 - Biological nitrification.

It has been observed that non-AWT factors can also exert very adverse effects on the successful operation of the AWT processes discussed herein, all other factors being equal. To address the technically related factors without also considering these factors could result in not achieving the level of success with these technologies that is possible.

APPENDIX A

IDENTIFIED PROBLEMS, IMPACTS, AND CAUSES

APPENDIX A

IDENTIFIED PROBLEMS, IMPACTS, AND CAUSES^a

<u>Identified Problem</u>	<u>Impact</u>	<u>Identified Cause^b</u>
<u>Tertiary lime, two-stage</u> Unable to raise process pH to desired level.	Insufficient phosphorus removal.	Lime feed system malfunctions (1,8,26)
<u>First-stage lime clarifiers</u> decommissioned.	Insufficient phosphorus removal.	Expansion joint leakage floods service gallery (6).
<u>Tertiary lime, single-stage</u> Solids contact clarification is sensitive to ratio of fresh lime to recirculated lime.	Labor-intensive operation. Solids carryover to ammonia stripping basins.	Unknown (5).
<u>Lime addition to raw wastewater</u> Unreliable flocculator drive mechanism.	Extended out-of-service periods. Labor-intensive repairs. Costly.	Carbonate accumulation on paddles increases load to drive train (4). Grit accumulation in basins (4).
Uneven settled solids accumulation in clarification section, or between multiple clarifiers.	Sludge withdrawal controls do not allow for variable withdrawal rate.	Uneven flow distribution to clarification section (4), or to clarifiers (17).
Skimming mechanism malfunctions.	Scum carryover to other processes.	Differential settling of flocculation-clarification basin (4).
Plant unable to meet effluent P content of 2 mg/L.	Exceeded permit limits.	Lime addition not appropriate for required P level (29).
Lime alone not adequate to flocculate solids ahead of activated carbon units.	Excess solids to adsorbers, leads to excess ΔP and backwash required.	Lime is inadequate coagulant; FeCl ₃ needed (23).
<u>Lime handling^c</u> Dust control.	Safety concerns. Labor-intensive operation.	Insufficient ventilation (1,6,38). Equipment malfunction (1,38).
Unreliable slaked lime delivery.	Improper lime dose. Labor-intensive operation.	Small diameter piping (1,4,5,8,14,26,40,17). Scale formation during off cycles (4). System configuration (8,21,38). Frequent slaker breakdown (30,21).
pH probe failures.	Improper lime dose. Labor-intensive repairs. Replacement costs.	Encrustation and clogging (4,5). Ruptures (4).
Unreliable recalcined or raw lime delivery.	Improper lime dose. Labor-intensive operation.	Metering facilities clog (6,7,8,14,43).
High raw lime grit content.	Mechanical wear. Improper lime dose. Labor-intensive operation. Equipment clogging. Control sensor interference.	Raw lime availability and cost (5,8). Pump selection (5). High rate of wear of slaker grit removal screw (38,40).

APPENDIX A (CONTINUED)

<u>Identified Problem</u>	<u>Impact</u>	<u>Identified Cause^b</u>
<u>Lime handling^c (continued)</u> Time delay between dosing signal and lime feed to process.	Improper lime dose.	Distance (250 feet) between slakers and rapid mix tanks (4).
Scale formation using recarbonation effluent as makeup water.	Labor-intensive operation. Inefficient slaking.	Incomplete recarbonation (4).
Lack of reliable fuel supply.	Recalciners not operable.	Fuel shortages (6).
Cost of lime and fuel.	Reluctance to operate processes.	Cost increases (4,5,6,7).
<u>Recarbonation/neutralization</u> <u>Inefficient CO₂ transfer to liquid phase.</u>	Incomplete recarbonation.	Coarse-bubble diffusers and/or inadequate tank depth (4).
Inadequate CO ₂ delivery rates.	Incomplete recarbonation. Labor-intensive repairs.	Flue gas delivery malfunctions (5,6,8). Carbon regeneration furnace not reliable as CO ₂ source (21).
Design pH reduction not achievable.	Incomplete recarbonation.	Insufficient CO ₂ delivery capacity (5).
Solids accumulation in basin.	Labor-intensive operation.	No solids collection mechanism (4,21). Excessive scaling of CaCO ₃ (40).
Acid pump seal failure.	Backup acid systems not available for neutralization.	Nonacid-resistant seal material (4).
<u>Lime sludge handling</u> <u>Inadequate lime withdrawal rate.</u>	Inhibits phosphorus removal and recarbonation steps.	Undersized sludge pumps and piping (8).
Scale formation in sludge transport piping.	Labor-intensive repairs. Inhibits phosphorus removal and recarbonation processes.	Intermittent sludge withdrawal (8).
Unreliable sludge decant.	Solids flow interrupted, affecting liquid treatment.	Decant pipe coupling material failure (4).
Variable solids feed to vacuum filters.	Variable dewatered solids content.	Solids separation and concentration in sludge storage tank combined with decant problems (4).
Filter cloth blinds.	Solids flow interrupted, affecting liquid treatment.	Improper filter cloth (4).
<u>Tertiary alum addition, separate stage</u> <u>Alum dose pump malfunction.</u>	Improper alum dose. Labor-intensive operation.	Pump design deficiency (2).
Alum sludge gravity thickeners decommissioned.	Thickener not cost-effective.	Thickeners not required for sludge handling (2).

APPENDIX A (CONTINUED)

Identified Problem	Impact	Identified Cause ^b
Ferric chloride addition to secondary turbidity control of $FeCl_3$ feed not effective.	Phosphorus removal criterion not met.	Turbidity meter not sufficiently sensitive (25).
Phostrip Potential for Nocardia foam.	Requires close process control.	Process restricts flexibility to manage activated sludge inventory (14).
Inflexible aeration control.	Requires close process control for Nocardia control.	Aeration rate reduction for Nocardia control can reduce phosphorus removal (14).
Nonapplicability of chlorination for Nocardia control.	Nocardia foam noncontrollable.	Chlorination increases effluent turbidity and TSS and reduces phosphorus removal capability (14).
High loadings and variability in phosphorus in influent.	Difficulty in control of effluent phosphorus loadings.	Sludge dewatering and organic sludge thickener release (anaerobically) phosphorus to sidestream recycle (22).
Plugging of orifices in reactor clarifier effluent weirs and stripper tank elutriate headers.	Increased operator time and maintenance.	Calcium carbonate scaling (22).
Interference of nitrates and nitrites in phosphorus uptake.	Reduced phosphorus removal efficiency.	Light loading on first stage activated sludge contributes to "premature" nitrification (30).
Biological nitrification ^d Inactive biological solids.	Nitrification deterioration.	Improper solids wasting procedures (7).
pH drops across process.	Nitrification deterioration.	Lime feed control inadequate (7). No alkalinity control facilities (13). Lime feed system clogging and failures (43).
Inadequate solids return rate.	Nitrification deterioration.	Undersized pump capacity (8).
Partial nitrification.	Effluent violations.	Variability in flow (10).
High level of solids sloughing.	Tertiary filters clog. Effluent suspended solids violations.	Seasonal load variations affect hydraulic loading control (13).
Higher D.O. than necessary in nitrification tanks.	Higher operating costs.	Excessive I/I causes washout (43,42). Lack of D.O. monitoring or control equipment (44).

APPENDIX A (CONTINUED)

<u>Identified Problem</u>	<u>Impact</u>	<u>Identified Cause^b</u>
<u>Ammonia stripping</u> NH ₃ reduction not achieved.	Effluent NH ₃ violations.	Limitations on stripper capacity (5).
Carbonate buildup on spray strippers.	Labor-intensive operation.	Design oversight (5).
Input pH highly variable.	Labor-intensive operation. Effluent NH ₃ violations.	Lime feed malfunction and/or inadequate clariflocculator performance (5).
<u>Microstrainers (secondary)</u> <u>Head box overflows.</u>	Causes by-pass, localized flooding.	Unit undersized (28).
Internal piping failures.	Unit performance impaired - effluent quality deteriorates.	Plastic piping could not withstand vibrations (28).
Filter fabric tears and separates.	Unit performance and effluent quality impaired.	Backwash nozzle location and intensity of backwash stream; method of securing fabric (28).
<u>Breakpoint chlorination</u> <u>System never operated.</u>	-	Failure of ammonia stripping process (5).
System did not meet design removal.	Exceeded effluent limits.	Excessive non-ammonia chlorine demand (21).
High residual chlorine concentrations.	Fish kill or chlorine criteria exceeded.	Pacing dose to reach breakpoint yielded high residual concentrations (6). Carbon dechlorination towers overflow (21).
Variable control on residual concentrations past breakpoint.	Process unreliability. Labor-intensive operation.	Sensitivity of process to dose and control procedures (6).
High cost.	Low affordability.	High chlorine doses (6,46).
<u>Ion exchange (climophilolite)</u> <u>Excessive loss of climophilolite during regeneration.</u>	Increased resin costs. Reduced exchange capacity.	Possible lack of proper control during backwash (40).
Loss of exchange bed capacity.	Reduced ammonia removal performance.	Inadequate regeneration, partly due to NaCl granules blocking under-drains (40).
Failure of wastewater piping.	Excessive maintenance and replacement costs.	FRP piping not adequately supported (40).
<u>Granular carbon system^c</u> <u>Underdrain structural failure.</u>	Process temporarily decommissioned.	Full design loads not anticipated (4). Underdrain not in accordance with engineer's specifications (6). Inappropriate installation (39).

APPENDIX A (CONTINUED)

<u>Identified Problem</u>	<u>Impact</u>	<u>Identified Cause</u> ^b
Granular carbon systems ^c (continued) BOD removal not achieved.	Unable to meet effluent limitations.	High level of nonadsorbable, soluble BOD in raw waste (4,48,25,21,18,46,17).
Sulfide generation.	Localized corrosion. Plant aesthetics.	BOD overload to system (4,21,18,17,48). Anaerobic conditions in adsorbers (48,21,18,46,17). Inadequate backwash capability (46,17).
Backwash or surface wash nozzles clog.	Labor-intensive operation.	Media migration to underdrain (4). Media plugging of nozzles (48).
Carbon transport pipe corrosion.	Costly repairs.	Use of steel pipe (4).
Carbon transport system clogs.	Labor-intensive operation.	Filter cone configuration restricts transport (9). Use of short-radius, 90° elbows and lack of cleanouts (39, 17). No eductors provided to slurry carbon (39). Slurry and quench water supply lines undersized (39).
Unreliable regeneration furnace exhaust system.	Labor-intensive repairs. Costly repairs.	Exhaust fan mechanical failures (4).
Unreliable spent carbon delivery to furnace.	Labor-intensive operation.	Furnace nozzle plugs (5). No means to fluidize dewatered carbon to feed to furnace (39,17), or to transfer regenerated carbon (40,17).
Spent carbon rotary feed malfunctions.	Labor-intensive operation.	Carbon fines clog mechanism (5).
Corrosion of adsorbers.	Costly repairs, potential unit failure.	Liner installation or material inadequate (48,17,40).
Upflow packed bed plugged.	Excessive pressure drop and channeling.	Separate backwash tank not effective (25).
Adsorber influent pipes ruptured.	Delay in startup. Replacement costs.	Thin-wall FRP pipe deteriorated; not adequately supported, and not adequate to pressure requirements (39).
Excessive carbon charring in regeneration furnace.	Loss of carbon and adsorption capacity.	Clogging of single regenerated carbon slurry pump (39).
Inadequate dechlorination following breakpoint chlorination for ammonia removal.	Excessive chlorine residuals in final effluent.	Carbon not as effective as dechlorinating agent as pilot testing indicated (46).

APPENDIX A (CONTINUED)

<u>Identified Problem</u> <u>Tertiary filtration</u> <u>Design hydraulic load not accepted.</u>	<u>Impact</u>	<u>Identified Cause</u> ^b
Media loss during backwash.	Floods filter. Unable to process plant flows.	Unknown--suspect uneven structural settling (4).
Backwash nozzles clog.	Labor-intensive operation.	Uneven air scour (4). Lack of rate limitation on backwash controls (13,21).
Frequent backwash failures.	Uneven backwash. Media loss. Labor-intensive operation.	Media migration to underdrain (6,10,20).
Backwash nozzle ruptures.	Labor-intensive operation.	Limited backwash storage volume (4,13). High rate of shaft erosion in backwash pumps (38).
Backwash nozzle corrosion.	Media migration to underdrain. Labor-intensive repairs.	Improper installation of plastic nozzles (6).
Underdrain tile grout.	Nozzles plug. Costly repairs. Labor-intensive repairs.	High chloride concentrations in raw waste corrode stainless steel (4).
Sensitive alum dose control.	Media migration to underdrain. Labor-intensive repairs.	Improper installation (6).
Media clogging.	Effluent turbidity excursions.	Stringent effluent turbidity requirements and direct filtration (3).
Filter valves stick.	Labor-intensive operation.	Incomplete recarbonation (8). Secondary solids carryover (28,21).
Inadequate surface agitation during backwash cycle.	Labor-intensive operation.	Equipment characteristics (13). Long delay in startup (39).
Excessive wear on laterals.	Bed surface not fluidized--poor backwash.	Poor installation--overly long construction period prevented aim rotation (39).
Filter not able to handle solids level in influent.	Accelerated replacement.	Location of backwash air scour diffusers causes "sand blasting" erosion (18).
Ozonation Air delivery malfunctions.	Effluent quality objectives not achieved.	Automatic backwash valve--less gravity filter misapplied to wastewater treatment (41).
Air drying malfunctions.	Process failure. Labor-intensive operation. Costly.	Blower bearing wear (10).
	Process failure. Labor-intensive operation. Costly.	Refrigerant dryer leaks freon (13). Dessicant life too short (13). Dessicant towers overloaded (13). Dessicant tower heating elements warped (13).

APPENDIX A (CONTINUED)

Identified Problem	Impact	Identified Cause ^b
Ozonation (continued) Electrical and control malfunctions.	Process failure. Labor-intensive operation.	Incompatible components (10,13). Insensitive hygrometer (13).
Generator tube breakage.	Process failure. Costly.	Moist air from improper drying (10,13). Cooling water leakage (5).
High ambient ozone concentrations inside buildings.	Unsafe working conditions.	Open ozone contactor installed inside building (13). General system leakage and design configuration (13).
Ozone delivery piping failure.	Costly repairs. High ambient ozone concentrations.	Nonozone-resistant PVC pipe (13). Nonwelded stainless steel pipe joints (13).
Porous ozone diffuser failures.	Process failure.	Nonozone-resistant epoxy used to attach diffusers (13).
Insufficient ozone transfer efficiency.	Process failure.	Insufficient contactor depths (13).
Instrumentation corrosion from off-gas.	Process failure. Costly repairs.	Uncovered contactor and corrodable instrumentation (5).
System complexity.	Labor-intensive operation.	Extensive system interdependence.
Lack of equipment service.	Process unreliability.	Manufacturer unreliability (10,13).
Process linkages ⁹ Secondary solids carryover to tertiary system.	Increases chemical dosages. Overloads tertiary filters. Labor-intensive operations.	Uneven mixed liquor and/or flow distribution in secondary system (2,3,9). Constraint on secondary solids removal capacity (6,42,28,23,21,34). Poor biological system control (3). Secondary clarifier short circuiting (1). Square secondary clarifier sweep arm disturbance (3). Secondary solids gasification (3). Periodic sloughing of RBC solids (28).

APPENDIX A (CONTINUED)

Identified Problem	Impact	Identified Cause ^b
Process linkages ^a (continued) Grease accumulation on tertiary filters.	Labor-intensive operation.	Mechanical failure of primary scum removal mechanism (9). Oil in raw waste--no primary clarification (13). Scum skimming failure from basin settlement (4).
Inadequate turbidity removal across tertiary filters.	Effluent turbidity violations.	Insufficient secondary oxygenation capacity (11).
High secondary BOD load to separate nitrification.	Reduced nitrification. Effluent NH ₃ excursions.	Shock organic loads to secondary system (12).
Insufficient secondary BOD load to separate nitrification.	Inadequate nitrification. Effluent NH ₃ excursions.	Improper control on secondary process (7).
Mechanical problems in primary, secondary, and pretreatment processes.	Overload plant personnel.	Various equipment-related problems (8).
Organic solids handling not reliable.	Labor-intensive operation which affects availability for liquid train.	Filter press malfunction (9). Mechanical problems (8).
Excess biological sludge production at low sludge age.	Increased sludge disposal costs and stress on sludge system capacity.	Mfr. recommended low sludge age to optimize Phostrip operation (22).
Higher than design influent loadings (BOD variability).	Increased load, "cascades" effect on AT processes.	Level and variability of loading apparently not anticipated (18).
Process recycle streams Biological process upset.	Tertiary performance reduced.	High organic load from heat treatment process (1). High pH in lime-conditioned filtrate (28).
Phosphorus loading increased.	Chemical dose control required.	Digester supernatant return (2,14,22).
Periodic activated sludge and nitrification upset.	Labor-intensive operation.	Cleaning flow equalization basins (9).
High temperature upsets biological and solids separation.	Effluent violations. Labor-intensive Solids carryover to tertiary units.	Inclinator scrubber water recycle (intermittent) (29). Regeneration scrubber water recycle (18).
Primary solids removal performance reduced by carbon fines recycle.	Solids carryover to downstream units.	Carbon regeneration scrubber water recycle (20).

APPENDIX A (CONTINUED)

<u>Identified Problem</u>	<u>Impact</u>	<u>Identified Cause</u> ^b
<u>Instrumentation</u> Unreliable signal to alum feed system.	Improper alum dose.	Signal tied to effluent meter, which fails repeatedly (2).
Multiple instrument suppliers.	Difficult spare parts stocking and more complicated maintenance.	Required "or-equal" clause in specs (44,42).
<u>Hydraulic loading</u> Flow exceeds design capacity.	Periodic effluent BOD and suspended solids violations.	Infiltration and inflow (1,2,9). Design capacity has been reached (8).
Wide flow variations.	Labor-intensive operation.	Seasonal loads from tourists (13).
<u>All Processes</u> Expiration of equipment guarantees before start-up.	No protection for owner for equipment malfunction.	Front-end purchase of equipment by contractor in long construction periods, with no provision in specs (44).
Multiple suppliers for same type of equipment.	Difficult spare parts stocking and more complicated maintenance.	Required "or-equal" clause in specs (43,42).
Equipment deterioration prior to start-up.	Equipment malfunctions and excessive O&M labor.	Excessive delays in construction completion (39).

^a Assessment of problems, impacts, and causes based on interviews with

^b Plant personnel and direct observations.

^c Plant codes are in parentheses.

^d Includes storage, recalcination, slaking, and delivery to process train.

^e Includes separate and combined nitrogen removal processes.

^f Includes carbon regeneration.

^g Gravity filters at all plants except Plants No. 13, 16, 22 (pressure).

^h Includes liquid and organic solids handling trains.

APPENDIX B

SUMMARY OF PLANT CHARACTERISTICS

APPENDIX B

SUMMARY OF PLANT CHARACTERISTICS

Plant Code	Key Process Characteristics	Average Flow, mgd		Key Effluent Limitations, mg/l ^a			
		Existing	Design	Parameter ^b	Criterion	Permit Conditions	Design
1	Air-activated sludge secondary. Two-stage lime tertiary, recarbonation, and mixed-media filtration.	13	20	BOD ₅ TSS Total phosphorus, as P	30-day ^c 30-day Percent removal	5 5 Maximum possible	- - -
2	Oxygen activated sludge secondary. Separate-stage alum tertiary and mixed-media filtration.	16	15	BOD ₅ TSS Total phosphorus, as P	30-day 30-day Percent removal	10 10 75	10 10 85
3	Roughing filters (oxidation towers). Air-activated sludge for combined BOD and nitrogen removal. Mixed-media direct filtration with alum.	11.5	15.6	BOD ₅ TSS NH ₃ , as N Turbidity, NTU	30-day 30-day 30-day Maximum	10 10 2 10	- - - -
4	Independent physical-chemical treatment. Lime addition to raw, degritted sewage with flocculation, sedimentation, recarbonation, granular activated carbon, and dual-media filtration. Carbon and filtration decommissioned. Acid neutralization replaces recarbonation.	10.0	12.5	BOD ₅ TSS	30-day 30-day	30 30	25 7
5	Water reclamation facility for groundwater recharge. Designed for secondary effluent clarification utilizing lime, with ammonia stripping, recarbonation, two-stage mixed-media filtration, ozonation, granular activated carbon, and breakpoint chlorination. Not currently utilized for recharge.	2.0	2.0	BOD ₅ COD Total nitrogen, as N Turbidity, NTU pH Chlorine	30-day 30-day 30-day Maximum Range Maximum	1.0 10.0 - 5.0 7.0-8.5 0.5	1.0 10.0 5.0 5.0 7.0-8.5 0.5

APPENDIX B (CONTINUED)

Plant Code	Key Process Characteristics	Average Flow, mgd		Key Effluent Limitations, mg/l ^a				
		Existing	Design	Parameter ^b	Criterion	Current Permit Conditions	Design	
6	Advanced treatment facility utilizing secondary effluent. Designed with two-stage line tertiary, recarbonation, mixed-media filtration, activated carbon, post-aeration, and breakpoint chlorination. Lime, carbon, post-aeration, and breakpoint chlorination not utilized.	25	30	BOD ₅	30-day ^c	3.0	3.0	
				TSS	30-day	3.0	-	
7 ^d	Biosludge for secondary. Separate, nitrification air-activated sludge, single-stage line tertiary, recarbonation, and mixed-media filtration.	4.5	10	Total Kjeldahl Nitrogen, as N	30-day	1.0	1.0	
				Total phosphorus, as P	30-day	0.2	0.2	
8	Oxidation towers for secondary. Separate nitrification air-activated sludge, single-stage line tertiary, recarbonation, and mixed-media filtration. Nitrification not currently required.	<15	10	Chlorine	Maximum	0.5	0.5	
				BOD ₅	30-day	15	15	
9	Air-activated sludge for combined BOD and nitrogen (single stage) removal. Sand filtration, granular activated carbon, and post-aeration. Nitrification, carbon, and post-aeration not currently required.	74	100	TSS	30-day	30	30	(e)
				NH ₃ , as N	30-day	(e)	(e)	
10	Air-activated sludge for combined BOD and nitrogen removal. Ozonation, flocculation with alum, and dual-media filtration.	5.7	6.7	Total phosphorus, as P	Maximum	5	1	
				BOD ₅	30-day	10	5	
11	Air-activated sludge secondary. Tertiary dual-media filtration following lagoons.	8.5	10	TSS	30-day	20	-	
				NH ₃ , as N	30-day	14	-	
12	Air-activated sludge secondary. Tertiary dual-media filtration following lagoons.	8.5	10	BOD ₅	30-day	20	-	
				TSS	30-day	15	-	
13	Air-activated sludge secondary. Tertiary dual-media filtration following lagoons.	8.5	10	NO ₃ + NO ₂ , as N	30-day	10	-	
				Turbidity, NTU	Maximum	2	-	

APPENDIX B (CONTINUED)

Plant Code	Key Process Characteristics	Average Flow, Mgd		Key Effluent Limitations, mg/l ^a			
		Existing	Design	Parameter ^b	Criterion	Permit Conditions	Design
12	Oxidation towers for secondary. Separate nitrification using rotating biological contactors.	2	3	BOD ₅ TSS ₂ NH ₃ -N	10-day ^c 30-day Maximum	20 30 10	-
13	Air-activated sludge secondary. Separate nitrification towers with pressure, mixed-media filtration, and ozonation. Ozonation decommissioned.	0.65	-	BOD ₅ TSS ₂ NH ₃ -N	10-day 30-day 30-day	30 30 10	5 5 10
14	Air-activated sludge for secondary with thiosulfate.	23.5	30	BOD ₅ TSS ₂ Total phosphorus, as P	10-day 30-day 10-day	10 20 0.55	-
15	Air activated sludge secondary ferrous sulfate and lime addition in secondary, separate nitrification, post-aeration.	2.5	5.5	BOD ₅ TSS ₂ TKN Phosphorus, as P	10-day ^g 30-day ^g 30-day (Summer) 30-day (Summer)	(95) ^h (95) ^h 0.2 0.8	(95) (95) 0.2 0.8
16	Biological nitrification, mixed-media gravity filtration, alum addition to nitrification effluent.	3.8	4.6	BOD ₅ TSS ₂ NH ₃ -N Total phosphorus, as P D.O.	Summer/Winter Summer/Winter Summer/Winter Summer/Winter Summer/Winter	5/15 7/15 1/- 1/- 6.0/6.0	5/15 7/15 1/- 1/- 6.0/6.0
17	Independent physical/chemical, alum and lime coagulation/sedimentation, granular activated carbon, re-aeration.	9.7	15.3	BOD ₅ TSS ₂ D.O.	30-day 30-day Minimum	8 8 5.0	8 8 5.0
18	Independent physical/chemical, alum or FeCl ₃ coagulation/sedimentation, sand filtration, granular activated carbon.	8.1	13	BOD ₅ TSS ₂ Phosphorus, as P BOD ₅ and SS	30-day 30-day 30-day Percent removal	30 30 1.0 85	10 14 1.0 90/86
19	Independent physical/chemical, alum and FeCl ₃ coagulation/sedimentation, sand filtration, granular activated carbon.	0.5	2.6	BOD ₅ TSS ₂ Phosphorus, as P pH	30-day 30-day 30-day Range	30 30 1.0 6-9	30 30 1.0 6-9

APPENDIX B (CONTINUED)

Plant Code	Key Process Characteristics	Average Flow, mgd		Key Effluent Limitations, mg/l ^a			
		Existing	Design	Parameter ^b	Criterion	Permit Conditions	Design
20	Independent physical/chemical, coagulation/sedimentation, microstrainers, granular activated carbon, breakpoint chlorination, dechlorination.	6.5	10	BOD ₅ TSS NH ₃ -N pH TOD	30-day ^c 30-day Daily Range Mass loading	30 30 5-4 6-9 (f)	10 13 - 6-9 (f)
21	Independent physical/chemical, chemical coagulation/sedimentation, recarbonation, multi-media filtration, granular activated carbon, breakpoint chlorination, dechlorination (GAC).	0.5	1.0	BOD ₅ TSS NH ₃ -N Phosphorus, as P	30-day 30-day Daily Daily	10 10 1.0 1.0	10 10 1.0 1.0
22	Oxygen activated sludge, separate bio-nitrification, sand filtration, Phostrip.	10	24	BOD ₅ TSS Phosphorus, as P TKN	30-day 30-day Daily Daily	12 15 1.0 4.0	10 10 1.0 4.0
23	Independent physical/chemical, FeCl ₃ and lime addition to primary, granular activated carbon.	0.125 (Winter) 0.35 (Summer)	0.5	BOD ₅ TSS pH	30-day 30-day Range	30 30 6-9	30 30 6-9
24	Air activated sludge, separate bio-nitrification, tertiary lime, multi-media filtration, de-chlorination/recarbonation.	8.6	10	BOD ₅ TSS NH ₃ -N	30-day 30-day 30-day	8 10 2	8 10 2
25	Independent physical/chemical, FeCl ₃ coagulation/sedimentation, granular activated carbon.	0.05	0.05	BOD ₅ Phosphorus, as P	Percent removal Daily	(95) ^h 1.0	(95) ^h 1.0
26	Combined air activated sludge/bio-nitrification, chemical (lime & FeCl ₃) to primary, multi-media filtration recarbonation.	1.0	2.3	BOD ₅ TSS NH ₃ -N Phosphorus, as P	30-day 30-day Daily Daily	30 30 - -	3 1.0
27	Air activated sludge, multi-media filtration, recarbonation.	3.3	4.0	BOD ₅ TSS NH ₃ -N	30-day 30-day 30-day (summer)	14 20 6	10 20 -

APPENDIX B (CONTINUED)

Plant Code	Key Process Characterizing	Average Flow, mgd		Parameter ^b	Key Effluent Limitations, mg/l ^a		
		Existing	Design		Criterion	Current	
						Permit Conditions	Design
28	Rotating biological contactors, lime or alum chemical coagulation/ sedimentation, microstrainers, re-aeration.	0.1	0.21	BOD ₅ TSS NH ₃ -N Phosphorus, as P D.O.	30-day ^c 30-day Summer/Winter 30-day Minimum	10 15 0.5/1.5 0.5 6.0	10 15 0.5/1.5 0.5 6.0
29	Air activated sludge, lime or FeCl ₃ addition to primary, multi-media filtration, granular activated carbon.	2.6	12.5	BOD ₅ TSS Phosphorus, as P	Summer/Winter 30-day 30-day	10/20 25 2	10 25 2
30	Trickling filter, separate bio-nitrification, chemical (alum) addition to primary and secondary, multi-media filtration.	1.3	2.75	BOD ₅ TSS NH ₃ -N Phosphorus, as P	30-day 30-day Summer/Winter 30-day	15 10 0.5/1.5 0.5	15 10 0.5 1.5
31	Extended aeration air activated sludge, sand filtration.	0.16	0.5	BOD ₅ TSS NH ₃ -N pH D.O.	30-day 30-day Summer/Winter Range Minimum	10 25 1.5/4.5 6 to 9 5.0	10 25 1.5/4.5 6 to 9 5.0
32	Precipitation, rotating biological contactors, alum and FeCl ₃ to secondary.	4.5	6.2	BOD ₅ TSS NH ₃ -N pH D.O.	30-day 30-day Summer/Winter Range Minimum	10 25 1.5/4.5 6 to 9 5.0	10 25 1.5/4.5 6 to 9 5.0
33	High rate air activated sludge, sand filtration, re-aeration.	4.0	8.0	BOD ₅ TSS D.O.	Summer/Winter 30-day	20/30 30 -	20/30 30 5.0
34	Air activated sludge, alum addition to secondary, sand filtration, separate bio-nitrification timers.	1.6	4.2	BOD ₅ TSS NH ₃ -N Phosphorus, as P	Summer/Winter 30-day Summer/Winter 30-day	10/20 25 1.5/4.5 2	10 15 - -

APPENDIX B (CONTINUED)

Plant Code	Key Process Characteristics	Average Flow, mgd		Key Effluent Limitations, mg/l ^d				
		Existing	Design	Parameter ^b	Criterion	Current		Design
						Permit Conditions	Conditions	
35	Alum to primary and secondary, trickling filter secondary, separate bio-nitrification, sand filtration.	0.9	1.7	BOD ₅ TSS NH ₃ -N Phosphorus, as P D.O.	30-day ^c 30-day Summer/Winter 30-day Minimum	13 30 1.25/3.75 2.0 5.0		10 10 1.0/3.0 1.0 -
36 ^h	Air activated sludge with FeCl ₃ , tertiary FeCl ₃ coagulation, multi-media filtration, de-chlorination.	30	36	BOD ₅ TSS Phosphorus, as P pH D.O. NH ₃ -N	30-day 30-day Summer/Winter Range Minimum	8 (3) ^h 8 (3) ^h 0.21/1.0 6 to 9 6.0 -		3 1 0.2/1.0 6 to 9 8.0 1.0
37	Air activated sludge, alum to primary, secondary and tertiary, separate bio-nitrification, dechlorination, re-aeration.	1.0	4.0	BOD ₅ TSS TKN Phosphorus, as P	30-day 30-day Summer 30-day	20 20 10 20		20 20 7 2
38	Air activated sludge, separate (second stage) bio-nitrification, tertiary alum coagulation, sand filtration, phosphor, de-chlorination (SO ₂), re-aeration.	9.2	15	BOD ₅ TSS Phosphorus, as P UOD ₁	30-day (winter) 30-day 30-day 30-day	10 - 0.3 20		10 10 0.3 -
39	Rotating biological contactors, granular activated carbon, FeCl ₃ coagulation/sedimentation, tertiary multi-media filtration, re-aeration.	32	54	BOD ₅ TSS Phosphorus, as P D.O.	30-day 30-day 30-day Minimum	40 (interim) 25 (interim) - -		3 3 0.2 6
40	Air Activated sludge with combined bio-nitrification, tertiary lime coagulation/sedimentation, recarbonation, multi-media filtration, granular activated carbon, AHRF (cineptitolite).	8.5	15	BOD ₅ TSS NH ₃ -N Phosphorus, as P COD MBAS Turbidity	Wkly avg. Wkly avg. Wkly avg. Wkly avg. Wkly avg. Wkly avg. Wkly avg.	1.0 1.0 1.0 0.1 10.0 0.1 0.4 JTV		1.0 1.0 1.0 0.1 10 - -

APPENDIX B (CONTINUED)

Plant Code	Key Process Characteristics	Average Flow, mgd		Parameter ^b	Key Effluent Limitations, mg/l ^d		
		Existing	Design		Criterion	Permit Conditions	Design
41	Activated sludge with powdered activated carbon (PACT), multi-media filtration, re-aeration.	6.5	12	BOD ₅ TSS ^a NH ₃ -N D.O.	Summer/winter Summer/winter Summer/winter Summer/winter	12/24 30/30 4/8 5/5	5 5 4 -
42	Air activated sludge, separate bio-nitrification, multi-media filtration.	2.2	3.5	BOD ₅ TSS ^a NH ₃ -N	30-day ^c 30-day 30-day	5 30 2	5 30 2
43	Two-stage trickling filters, separate (pure oxygen) bio-nitrification, multi-media filtration, re-aeration.	2.3	4.1	BOD ₅ TSS ^a NH ₃ -N Phosphorus, as P	30-day 30-day 30-day -	8 30 2 -	8 30 2 2
44	Air activated sludge with combined bio-nitrification, alum or FeCl ₃ addition to aeration tanks, effluent stabilization ponds, re-aeration.	35	60	BOD ₅ TSS ^a NH ₃ -N Phosphorus, as P D.O.	Wkly Avg. Wkly avg. Summer/winter Wkly avg. Minimum	10 10 1.1/2.2 1 5	- - - - -
45	Air activated sludge with combined bio-nitrification, FeCl ₃ coagulation/sedimentation.	9.5	10.5	BOD ₅ TSS ^a NH ₃ -N Phosphorus, as P Oil & grease Cadmium Chromium Copper Lead Mercury Zinc	30-day 30-day Summer/winter 30-day 30-day µg/L-any time µg/L-any time µg/L-any time µg/L-any time µg/L-any time µg/L-any time	10 12 1.0/1.5 1.5 5 12 100 115 30 0.2 320	- - - - - - - - - - -
46	Independent physical/chemical FeCl ₃ /lime coagulation/sedimentation, multi-media filtration, granular activated carbon, breakpoint chlorination, dechlorination (GAC), re-aeration.	3.75	6	BOD ₅ TSS ^a Phosphorus, as P D.O.	Summer/winter Summer/winter Summer - 30-day Minimum	7/30 20/30 2 4	6 15 1 -

APPENDIX B (CONTINUED)

Plant Code	Key Process Characteristics	Average Flow, mgd		Key Effluent Limitations, mg/l ^d			
		Existing	Design	Parameter ^b	Criterion	Permit Conditions	Design
47	Independent physical/chemical, FeCl ₃ /lime coagulation/sedimentation, multi-media filtration, granular activated carbon, 2nd-stage multi-media filtration, ABRP (clinoptilolite).	0.3	0.6	BOD ₅	30-day ^c	25	10
				TSS	30-day	30	10
				Phosphorus, as P	30-day	1	1
				NH ₃ -N	-	-	1
48	Independent physical/chemical, FeCl ₃ /lime coagulation/sedimentation, granular activated carbon.	11	16	BOD ₅	30-day	60	-
				TSS	30-day	60	-

^a Concentrations are in mg/l, unless noted otherwise. Existing limitations tabulated are the most stringent current requirements. Design limitations are those established for plant design. Only parameters related to advanced treatment are tabulated. Chlorination and dechlorination are not included.

^b Unless noted otherwise, all plants must meet a pH limitation of 6.0 to 9.0.

^c 30-day = 30-day average value. Maximum = daily or instantaneous maximum value.

^d Existing limitations shown are proposed values.

^e Initial design and effluent limitations required a 21-day BOD less than or equal to 15 mg/l.

^f TOD loading based on stream flow and temperature.

^g Based on percent removal.

^h Limitations in parentheses are permit limits prior to March 1983 (consent order).

ⁱ Year-round limit prior to March 1983.

^j BOD = 1.5 (BOD₅) + 4.6 (TSS).

APPENDIX C

SUMMARY OF PLANTS BY ADVANCED
TREATMENT TECHNOLOGIES

APPENDIX C

SUMMARY OF PLANTS BY ADVANCED TREATMENT TECHNOLOGIES

<u>AWT Technology</u>	<u>Plant Code</u>
Granular activated carbon	4, 5, 6, 9, 17, 18, 19, 20, 21, 23, 25, 29, 39, 40, 46, 47, 48
Tertiary filtration (gravity)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 21, 22, 24, 27, 29, 30, 31, 34, 35, 36, 38, 39, 40, 42, 43, 46, 47
Tertiary filtration (pressure)	13, 16, 33
Intermediate filtration (gravity)	18, 19
Recarbonation	1, 4, 5, 6, 7, 8, 21, 40
Biological nitrification (combined)	3, 9, 10, 16, 26, 35, 40, 44, 45
Biological nitrification (separate stage)	7, 8, 12, 13, 15, 16, 22, 24, 30, 32, 34, 37, 38, 42, 43
Lime (primary) single and two-stage	4, 17, 20, 23, 24, 26, 29, 37, 38, 40
Lime (tertiary) single-stage	1, 5, 6, 7, 8, 16
Alum (primary)	16, 17, 19, 28, 37, 38
Alum (secondary)	16, 30, 34, 35, 37
Alum (tertiary)	2, 3, 10, 37
Ferric (primary)	18, 19, 23, 25, 26, 28, 29, 36
Ferric (tertiary)	36, 38, 39, 44, 45, 46, 47
Microstrainers	20, 28
Breakpoint chlorination	5, 6, 20, 21, 36, 46
PACT process	41
Post-aeration	6, 9, 15, 16, 26, 27, 28, 36, 37, 38, 39, 41, 43, 46

APPENDIX C
(CONTINUED)

<u>AWT Technology</u>	<u>Plant Code</u>
Ammonia stripping	5
Other chemical addition	17, 18, 19, 21, 25, 37, 38, 39, 47
Dechlorination	20, 21, 36, 37, 38, 46
PhoStrip	14, 22, 38
Neutralization	4, 25
Clinoptilolite (ARRP)	40, 47
Ozonation	5, 10, 13